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PHOSPHORUS REMOVAL EFFICIENCY UPGRADING AT MUNICIPAL WASTEWATER TREATMENT PLANTS IN THE GREAT LAKES BASIN

PHASE 3
PERFORMANCE
INPROVEMENTS

Technical Report

FEBRUARY 1988

Canada Ontario

Canada-Ontario Agreement Respecting Great Lakes Water Quality
L'Accord Canada-Ontario relatif à la qualité de l'eau dans les Grand Lacs

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1.0 INTRODUCTION

This three-phase study program was undertaken to identify the most cost-effective phosphorus management strategy to meet the phosphorus loading reduction objectives of the Ontario Ministry of the Environment (MOE). The initial phase of the program involved an in-depth review of historical plant performance data for municipal water pollution control plants (WPCPs) in the Great Lakes drainage basin with design flows greater than 4545 m^3/day. A preliminary assessment of the alternative management strategies available was also undertaken. The results of this component of the investigation were presented to MOE in a Phase 1 report in November 1986[1].

Phase 2 of the study program involved field evaluations at selected WPCPs to establish the critical factors affecting phosphorus removal performance. Twelve facilities were selected based on the historical data review undertaken in Phase 1. Five plants were included which had demonstrated superior phosphorus removal performance - Port Dalhousie WPCP, Fergus WPCP, Midland WPCP, Port Hope WPCP and Trenton WPCP. Seven plants were included which had consistently had difficulty complying with the 1 mg/L total phosphorus requirement - Collingwood WPCP, Moore Township (Corunna) WPCP, St. Thomas WPCP, Toronto Humber WPCP, Toronto Main WPCP, Duffin Creek WPCP and Esten Lake WPCP. The results of these field evaluations were presented to MOE in a Phase 2 report in February 1987[2].

Phase 3 of the study program was intended to demonstrate that phosphorus removal performance improvements could be cost-effectively achieved in most cases by low capital cost measures. Several plants which had been evaluated in Phase 2 were selected for more detailed investigation during the Phase 3 portion of the study. The Phase 3 program is described in more detail in the following subsection. The results of the Phase 3 investigations are then presented in subsequent sections of this report.

1.1 Phase 3 Program

1.1.1 Objectives

The results of the Phase 1 and Phase 2 investigations, as well as previous experience in phosphorus removal assessments[3], showed that the

most significant factor contributing to consistent non-compliance with effluent phosphorus limits was inadequate chemical dosage. Inadequate sludge management practices and high clarifier surface loadings were identified as secondary factors contributing to plant non-compliance; however, in some cases, high chemical dosage can effectively compensate for problems related to poor sludge management or high hydraulic loading.

The overall objective of the Phase 3 program was to demonstrate that phosphorus removal performance could be upgraded by low capital cost operational changes, in most cases. Four plants were selected for more detailed assessment in Phase 3 - Collingwood WPCP, Duffin Creek WPCP, Toronto Humber WPCP, and Toronto Main WPCP. Collingwood and Duffin Creek WPCPs were included in Phase 3 because the Phase 2 data suggested that improvements in phosphorus removal performance could be achieved at these plants. The Toronto Humber and Toronto Main WPCPs were included in Phase 2 because of the magnitude of their phosphorus loading contribution to the Great Lakes Basin.

1.1.2 Program Description

The investigations conducted at the Collingwood WPCP and Duffin Creek WPCP were similar in that operational changes had been made at the plants subsequent to the Phase 2 investigations to correct chemical dosage inadequacies. The Phase 3 program at both of these facilities involved extended monitoring of plant performance and optimization of operating conditions to document the success of these operational changes. Details of these studies are presented in Sections 2.0 and 3.0 of the report, respectively.

The Phase 2 studies at the two Toronto plants (Main and Humber) were conducted during periods of high flow due to abnormally high precipitation. Therefore, these results were not considered to be typical of plant performance under normal flow conditions and did not conclusively identify the long-term problems at these plants which prevented consistent compliance with the 1 mg/L effluent total phosphorus limit. Thus, the Phase 3 evaluations at these plants focussed on an intensive analysis of historic plant operating and performance data. The results of these investigations were utilized to define the specific causes of phosphorus removal inadequacies and to establish if additional on-site Phase 3 work at these plants was necessary. The results of these studies are presented in Section 4.0 (Toronto Main) and Section 5.0 (Toronto Humber).

2.0 COLLINGWOOD WPCP

2.1 Background

2.1.1 Plant Description

The Collingwood WPCP is a conventional activated sludge plant with a design hydraulic capacity of 24,550 m^3/d. Detailed design data were presented in the Phase 2 report(2). A schematic flowsheet of the plant is reproduced as Figure 1. Phosphorus removal had been achieved by dual point alum addition to the aerated grit tanks and the mixed liquor upstream of the secondary clarifiers. The chemical feed to the aerated grit tanks was discontinued prior to the Phase 3 program.

2.1.2 Historical Performance

The Collingwood WPCP has historically had difficulty in consistently meeting the effluent total phosphorus limit of 1 mg/L. As shown in Table 1, the average concentration for the years 1982 (when the secondary facility became operational) to 1985 was 1.42 mg/L. The plant did not comply with the effluent objective of 1 mg/L for eighteen (78 percent) of the 23 months reported in 1984 and 1985, despite producing a high quality effluent in terms of BOD_5 (1982-1985 average = 9.2 mg/L) and suspended solids (1982-1985 average = 13.3 mg/L).

TABLE 1. ANNUAL AVERAGE PERFORMANCE OF COLLINGWOOD WPCP

PARAMETER	YEAR					5 YEAR AVERAGE 1981-1985
	1981	1982	1983	1984	1985	
Avg. Daily Flow (1000 m^3	15.91	15.28	17.86	17.38	18.54	16.83
BOD_5 - Influent (mg/L)	-	193.0	200.0	134.3	163.3	170.2
BOD_5 - Effluent (mg/L)	70.0	15.0	8.0	7.9	5.8	9.2*
TSS - Influent (mg/L)	112.0	192.0	154.0	165.7	131.1	150.9
TSS - Effluent (mg/L)	42.0	15.0	10.2	15.3	12.6	13.3*
Total P - Influent (mg/L)	5.10	6.40	5.59	10.21	11.18	7.76
Total P - Effluent (mg/L)	1.85	0.60	1.65	1.49	1.92	1.42*

* Only 1982-1985 included in average.

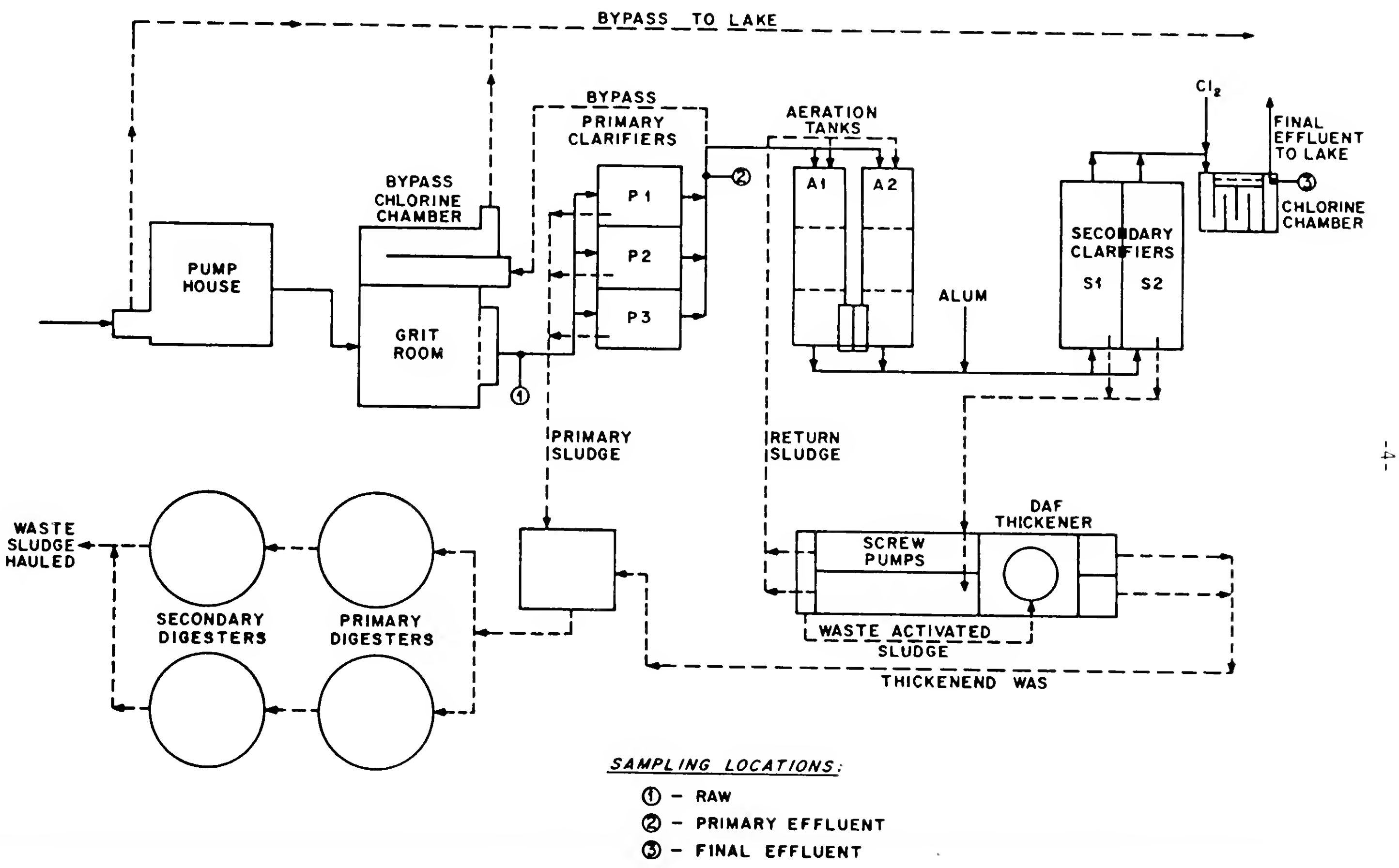


FIGURE 1 : SCHEMATIC OF COLLINGWOOD WPCP

2.1.3 Phase 2 Performance

The Collingwood WPCP was monitored for a one-month period between June 15 and July 15, 1986 and the performance data confirmed the historic results, as summarized in Table 2. The plant produced a high quality effluent in terms of BOD_5 and suspended solids, but did not achieve an effluent total phosphorus level of less than 1 mg/L. A large fraction of the phosphorus discharged to the final effluent was present in soluble form.

TABLE 2. SUMMARY OF PHASE 2 SAMPLING RESULTS

	BOD_5 (mg/L)	TSS (mg/L)	PHOSPHORUS (mg/L)	
			TOTAL	SOLUBLE
Influent	145	178	13.7	10.6
Effluent	2	7	1.50	1.10

The Phase 2 monitoring results showed that the alum dosage at the plant was relatively high at approximately 8 mg Al/L based on plant records. However, the dosage, calculated as a molar metal-to-phosphorus (Al:P) ratio, was low (0.94) due to the high influent phosphorus concentration (13.7 mg/L). Further, it was determined during Phase 3 (refer to Section 2.4.3) that the plant had been overestimating the alum usage rate and the dosage by up to 25 percent. The plant was also exposed to occasional extreme influent phosphorus concentrations due to industrial discharges. Plant staff had no means of identifying high influent levels and the chemical dosage was inadequate to precipitate these high influent phosphorus concentrations.

2.1.4 Problem Identification

The Phase 2 monitoring data did not suggest the presence of phosphorus compounds which were not amenable to precipitation but rather an inadequacy of chemical dosage to handle the influent phosphorus concentration

experienced at the plant. The dual point addition approach used during Phase 2 did not appear to significantly improve phosphorus removal efficiency at the plant. To achieve the 1 mg/L effluent total phosphorus objective on a consistent basis would require a significant increase in alum usage and, even under these operating conditions, short term excursions would be expected during periods of abnormally high (>20 mg/L) influent phosphorus concentrations.

Three major industries in the Town of Collingwood had been identified as being major contributors to the treatment facility - a starch plant (7 percent of hydraulic load), a glass manufacturing plant (9 percent of hydraulic load) and a distillery (8 percent of hydraulic load). Two of these industries had been identified as also being major sources of phosphorus, based on town sewer monitoring programs - the starch plant during production of phosphorylated starches and the glass plant from glass washing operations. A significant fraction of the WPCP phosphorus loading was attributable to these sources.

2.2 Phase 3 Program

2.2.1 Approach

In the late fall of 1986, the two large industrial contributors began to initiate in-house steps to reduce phosphorus discharges to the sanitary sewer at the direction of the Town of Collingwood. These steps were intended to be complete by the beginning of February 1987. At the same time, plant staff discontinued alum addition to the aerated grit tanks and began dosing all chemical to the mixed liquor upstream of the secondary clarifier. As town staff had already initiated measures to reduce the influent phosphorus concentrations to more typical levels, a Phase 3 monitoring program was initiated to optimize chemical dosage and document that an effluent total phosphorus concentration of less than 1 mg/L could be achieved on a consistent basis. At the same time, town and MOE Regional staff requested that the sludge management practices at the plant be reviewed, particularly as they impacted on phosphorus removal capability.

2.2.2 Monitoring Program

The Phase 3 monitoring program was similar in nature to the Phase 2 program. Automatic 24-hour composite samplers were installed on the plant influent, primary effluent and final effluent. The emphasis of the program was placed on final effluent quality, to document plant performance, and on primary effluent quality, to document chemical dosage on a metal-to-phosphorus ratio basis. Less intensive sampling was done on raw sewage to verify that the industrial waste management programs had successfully reduced influent phosphorus levels. At the start of the Phase 3 program, the bulk of the analytical work was conducted by plant staff, with CANVIRO analyses to verify plant data. During the course of the Phase 3 program, analytical inconsistencies were identified in the plant data and, thereafter, all analytical work was done at the CANVIRO laboratory in Kitchener (refer to Section 2.4.2). The performance results reported are based on CANVIRO analytical data only.

The monitoring program was initiated on February 2, 1987 and was completed on March 31, 1987, resulting in approximately 8 weeks of monitoring data. The initial ten days of the program were used to establish the influent phosphorus concentration after the industrial contribution had been reduced and to define the chemical dosage requirements. During this period, most analyses were conducted by plant staff. Subsequently, optimization of chemical dosage was undertaken and performance evaluated on the basis of CANVIRO analytical data. Through the Phase 3 monitoring, data defining plant operating conditions (flow, chemical dosage, sludge wastage, etc.) were routinely collected by plant staff.

2.3 Phase 3 Results

2.3.1 Raw Sewage Quality

Results of Phase 2 and Phase 3 raw sewage samplings are compared in Table 3 in terms of concentrations of total and filtered phosphorus, suspended solids and BOD_5. Waste strength, in terms of all parameters, was lower during the Phase 3 program than during the Phase 2 program. The average daily flow during Phase 3 was 16,500 m^3/d, compared to 17,440 m^3/d during Phase 2. Dilution due to rainfall and spring runoff during Phase 3 does not

TABLE 3. COMPARISON OF RAW SEWAGE QUALITY DURING PHASE 2 AND PHASE 3 MONITORING

	BOD_5 (mg/L)	TSS (mg/L)	PHOSPHORUS (mg/L)	
			TOTAL	SOLUBLE
Phase 2 *	145	178	13.7	10.6
Phase 3 **	120	106	4.9	3.3

* Based on 11 sampling days between June 18 and July 15, 1986.

** Based on sampling period between February 1 and March 31, 1987 (BOD_5 - 20 samples; TSS - 36 samples; phosphorus - 11 samples).

appear to be a significant contributor to the reduction in sewage strength as flows during the two sampling periods were comparable. The in-plant measures instituted by the large industrial contributors to reduce phosphorus discharges may have also reduced discharges of BOD_5 and suspended solids.

The industrial phosphorus discharge control program had a marked effect on influent phosphorus concentrations at the plant. The concentration measured during Phase 3 was only 36 percent of that experienced during the Phase 2 monitoring period.

Discrete samples were collected at two hour intervals for up to 24 hours on three occasions during Phase 3 to determine if the plant was experiencing short term peak phosphorus concentrations due to batch discharges. These results showed no significant short term peak loads.

2.3.2 Plant Operation

Table 4 summarizes key operational data for the Collingwood WPCP during the Phase 3 monitoring period. Alum dosages presented in Table 4 reflect the corrected dosage based on actual chemical usage for the period. As noted previously, alum was added only to the aeration tank discharge during Phase 3. The average dosage during Phase 3 was 7.4 mg/L Al/L, comparable to the estimated dosage of 8 mg/L during Phase 2. The flow-proportioning capability of the alum feed system was not used during Phase 3 due to mechanical problems.

TABLE 4. SUMMARY OF PHASE 3 PLANT OPERATING CONDITIONS

DATE	FLOW (m^3/d)	M L S S			W A S		SRT (days)	F : M (g/g.d)	ALUM USED (kg)	DOSAGE (mg Al/L)
		SOUTH (mg/L)	NORTH (mg/L)	VOLATILE %	(mg/L)	(m^3/d)				
Feb 1	12,860								890	6.3
2	12,441	3880	4820		8768			0.030	1040	7.6
3	13,120	3952	4592		8200			0.079	960	6.7
4	14,092	4096	4280	68.0	8748				960	6.2
5	13,486	4040	4360		6440			0.096	960	6.5
6	13,214								1200	8.3
7	13,757								1200	7.9
8	13,595								1200	8.0
9	13,331								1320	9.0
10	14,557	4136	4728		8792			0.060	960	6.0
11	14,538	3240	4708	69.6	9020	222	19.8	0.075	600	3.8
12	14,758	4084	4712		8076			0.060	1680	10.3
13	15,048	3388	4720		8688			0.060	840	5.1
14	13,867								1200	7.9
15	13,410								1200	8.1
16	13,285	3360	4628	70.3	8996	186	13.9	0.080	960	6.6
17	14,391	3560	4332		9428			0.061	1180	7.5
18	14,799	3332	4292	67.2	10040	120	18.4	0.083	1040	6.4
19	13,598	3100	4320		9880			0.067	1110	7.4
20	14,082	3152	4400		9236			0.045	1110	7.2
21	14,397								590	3.7
22	13,785								1550	10.2
23	13,745	3200	4272	68.6	4648	135	18.7	0.069	1110	7.3
24	14,831	3068	4048		9536			0.086	960	5.9
25	14,667	2828	4048	67.7	9676	125	16.6	0.086	1180	7.3
26	14,885	3344	4468		9308			0.105	1040	6.4
27	14,423	3300	4052		10360			0.036	1040	6.6
28	15,083								890	5.4
Mar 1	15,420								590	3.5
2	19,330	2800	3708		11120			0.092	480	2.3
3	19,268	3174	4232	69.4	12612	105	16.3	0.112	480	2.3
4	17,560	3016	3880		10248			0.157	600	3.1
5	17,360								2160	11.3
6	17,292								1560	8.2
7	22,109								2040	8.4
8	28,590								1680	5.3
9	25,840								480	1.7
10	24,090	2472	2844	70.9	10236	126	12.0	0.073	720	2.7
11	21765	2596	2968		9200			0.101	960	4.0
12	19,234	2728	3556		10388			0.042	1200	5.7
13	18,334	2668	3400		9872			0.027	1560	7.7
14	17,961								1850	9.4
15	17,280								1700	8.9
16	16,340	2824	3888	70.0	9564	137	14.9	0.077	1780	9.9
17	17,932	2872	3692	70.2	7920	166	14.6	0.056	1780	9.0
18	17,135	3280	3960		9200			0.061	1700	9.0
19	17,629	3460	4116		8856			0.064	2070	10.7
20	15,876	3504	4008		8340			0.030	2070	11.8
21	17,010								2070	11.1
22	15,335								1860	11.0
23	15,943	3268	4560	67.5	8280	168	16.4	0.037	1920	10.9
24	18,624	4160	4260		8444			0.034	1680	8.2
25	15,533	3596	3968		9712			0.049	2160	12.6
26	18,000	3512	4016		10104				1920	9.7
27	18,254	3352	3812		10212			0.024	1920	9.6
28	17,520								1920	10.0
29	16,967								1920	10.3
30	17,936	3096	3868		9680				1920	9.7
31	23,637	3372	3672		8200			0.075	2070	8.0
AVERAGE	16,502	3320	4105	69.0	9298	137	16.2	0.067	1335	7.4

Notes: WAS volume is estimated based on WAS concentration and DAF float volume and concentration.
SRT is estimated based on calculated WAS volume.
F:M is calculated in terms of primary effluent total BOD_5 concentration and average MLSS.
'SOUTH' is denoted as A1 in Figure 1.
'NORTH' is denoted as A2 in Figure 2.

As noted during Phase 2, the plant maintains a high biomass inventory in the aeration tanks, resulting in a long SRT (approximately 16 days) and a low F/M ratio (0.067 g BOD/g SS·d). Despite the low loadings, excellent sludge settleability characteristics are achieved. SVI's in the plant ranged between 80 and 130 mL/g during Phase 3. The north aeration tank has consistently contained higher mixed liquor concentrations than the south tank, due to an unequal split of either the return sludge or primary effluent flows between the two tanks.

Final effluent quality during February and March is presented in Table 5. Effluent BOD_5 was consistently less than 25 mg/L and averaged approximately 5 mg/L. Final effluent suspended solids were high compared to historical data, averaging 16.6 mg/L. The high average TSS concentration relates to two plant upsets. On March 2, a mechanical problem caused all the flow to pass through one of the two secondary clarifiers, creating a hydraulic overload and a loss of solids to the final effluent. On March 31, a rainfall event created a short term flow peak which resulted in carryover of the sludge blanket. Clarifier surface loadings exceeded 32 $m^3/m^2·d$ and sludge loading exceeded 7 $kg/m^2·d$ on this occasion. Exclusive of these two events, the average concentration was 12 mg/L. The 90 percentile concentration for the period February/March was 34 mg/L, according to the probability distribution of effluent quality shown in Figure 2.

The average final effluent total phosphorus concentration was less than 0.50 mg/L over the Phase 3 monitoring period despite the upset event on March 31 when the total phosphorus concentration was 3.8 mg/L due to the suspended solids carryover. The 90 percentile concentration for the period February/March was 0.95 mg/L, according to the probability distribution presented in Figure 2.

2.3.3 Phosphorus Removal Performance

Key operating parameters affecting phosphorus removal at the plant are summarized in Table 6 for the Phase 3 monitoring period. Probability distributions of primary effluent and final effluent total and filtered phosphorus are presented in Figure 3. The primary effluent data confirm the reduction in raw sewage strength compared to historical data. Average primary effluent total phosphorus during Phase 3 was 4.4 mg/L, compared to 8.8 mg/L

TABLE 5. FINAL EFFLUENT QUALITY DURING PHASE 3

DATE		FINAL EFFLUENT CONCENTRATION (mg/L)		
		BOD_5	TSS	TOTAL P
Feb	2	3	8	
	3	4	12	0.31
	4		11	
	5	5	19	
	6	4		
	9	18		
	10		12	
	11		4	
	12	3	18	
	13	4	3	0.40
	16	1	9	
	17	1	4	<0.23
	18	6	3	<0.23
	19	1	5	<0.24
	20	2	11	<0.23
	23	5	14	
	24	6	23	0.82
	25	4	24	1.20
	26	5	7	0.34
Mar	2	7	50	
	3	9	22	0.68
	4	15	26	0.48
	5	8		<0.30
	10	5	26	0.30
	11	5	10	0.24
	12	5	9	<0.25
	13	2	11	<0.30
	16	2	5	<0.23
	17	2	10	<0.23
	18	2	5	<0.23
	19	1	11	<0.23
	20	1	8	0.28
	23	2	2	0.24
	24	3	33	0.66
	25	2	12	<0.26
	26		10	
	27	1	4	<0.23
	31	17	142	3.80
Apr	1	2	-	0.29
AVERAGE		4.6	16.6	<0.49

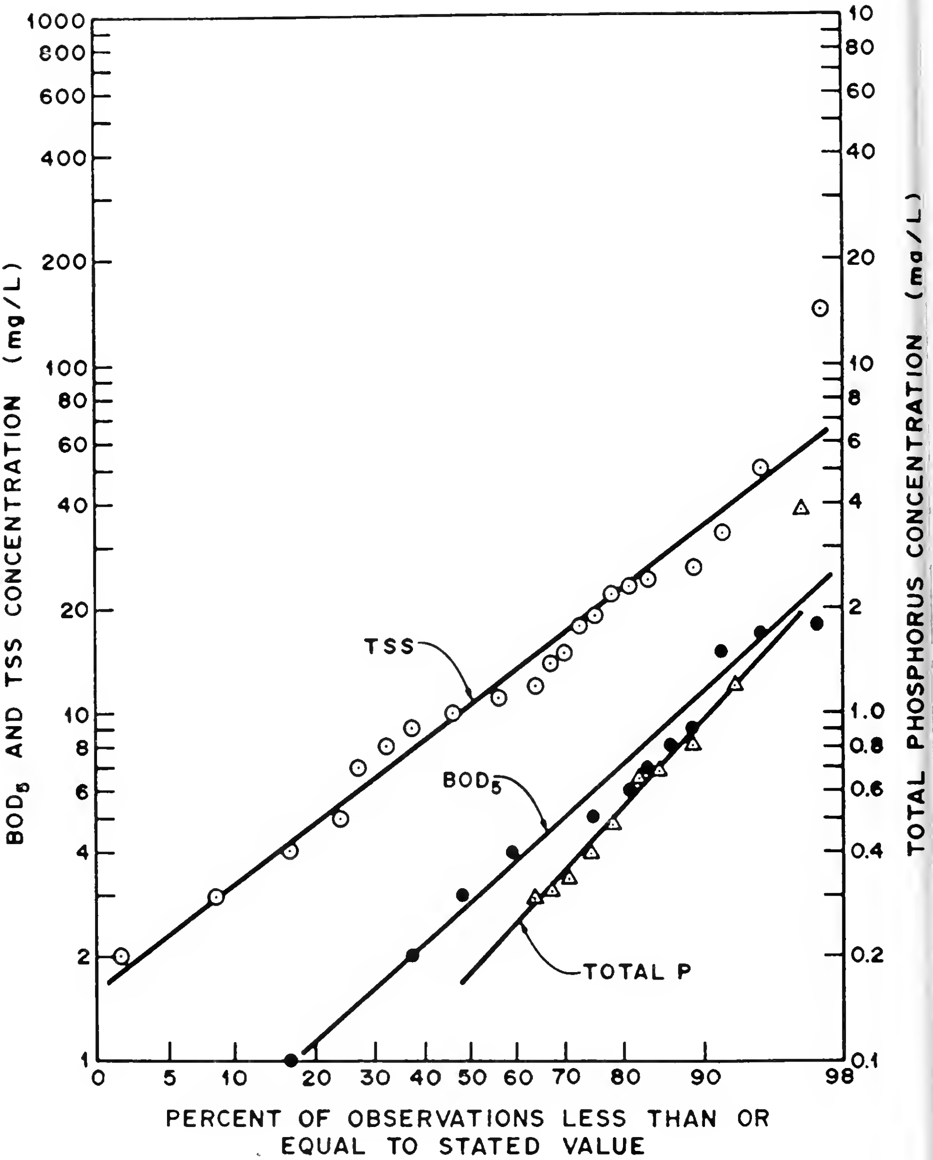


FIGURE 2: FREQUENCY DISTRIBUTION OF EFFLUENT QUALITY

TABLE 6. KEY OPERATING PARAMETERS AFFECTING PHOSPHORUS REMOVAL DURING PHASE 3

DATE	FLOW (m^3/d)	PRIMARY EFFLUENT (mg/L)		ALUM DOSE (mg Al/L)	Al:P RATIO *		EFFLUENT QUALITY (mg/L)			
		TOTAL P	FILTERED P		WT.	MOLAR	TSS	TP	SOL. P	PART. P
Feb 17	14,391	4.6	4.4	7.5	1.70	1.96	4	<0.23	<0.23	-
18	14,799	5.0	3.1	6.4	2.06	2.37	3	<0.23	<0.23	-
19	13,598	4.8	3.4	7.4	2.18	2.50	5	<0.23	<0.31	-
20	14,082	4.5	3.1	7.2	2.32	2.67	11	<0.23	<0.23	-
24	14,831	3.5	3.2	5.9	1.84	2.12	23	0.82	<0.23	>0.59
25	14,667	6.3	3.3	7.3	2.21	2.54	24	1.20	<0.26	>0.94
26	14,885	5.7	3.4	6.4	1.88	2.16	7	0.34	<0.23	>0.09
Mar 3	19,268	3.5	2.0	2.3	1.15	1.32	22	0.68	<0.21	>0.47
5	17,360	3.0	2.0	11.3	5.65	6.49	-	<0.30	<0.44	-
10	24,090	3.4	1.8	2.7	1.50	1.73	26	0.30	<0.19	>0.11
11	21,765	3.3	2.3	4.0	1.74	2.00	10	0.24	<0.21	>0.03
12	19,234	2.7	1.5	5.7	3.80	4.37	9	<0.25	<0.25	-
13	18,334	3.3	2.2	7.7	3.50	4.03	11	<0.30	<0.21	-
14	17,961	2.0	1.0	9.4	9.40	10.81	-	0.25	<0.22	>0.03
15	17,280	2.4	1.2	8.9	7.42	8.53	-	<0.23	<0.22	-
16	16,340	7.4	3.9	9.9	2.54	2.92	5	<0.23	<0.22	-
17	17,932	5.4	2.4	9.0	3.75	4.31	10	<0.23	<0.21	-
18	17,135	3.6	2.4	9.0	3.75	4.31	5	<0.23	<0.21	-
19	17,629	4.5	2.2	10.7	4.86	5.59	11	<0.23	<0.21	-
20	15,876	4.5	2.8	11.8	4.21	4.85	8	0.28	<0.19	>0.09
23	15,943	3.6	2.0	10.9	5.45	6.27	2	0.24	<0.22	>0.02
24	18,624	3.1	2.2	8.2	3.73	4.29	33	0.66	<0.22	>0.44
25	15,533	5.1	1.7	12.6	7.41	8.52	12	<0.26	<0.26	-
27	18,254	4.2	2.2	9.6	4.36	5.02	4	<0.23	<0.25	-
31	23,637	3.9	1.3	8.0	6.15	7.08	142	3.80	<0.24	>3.56
AVERAGE	17,346	4.3	2.5	7.8	3.68	4.23	18	<0.49	-	-

* Based on filtered phosphorus concentration in primary effluent.

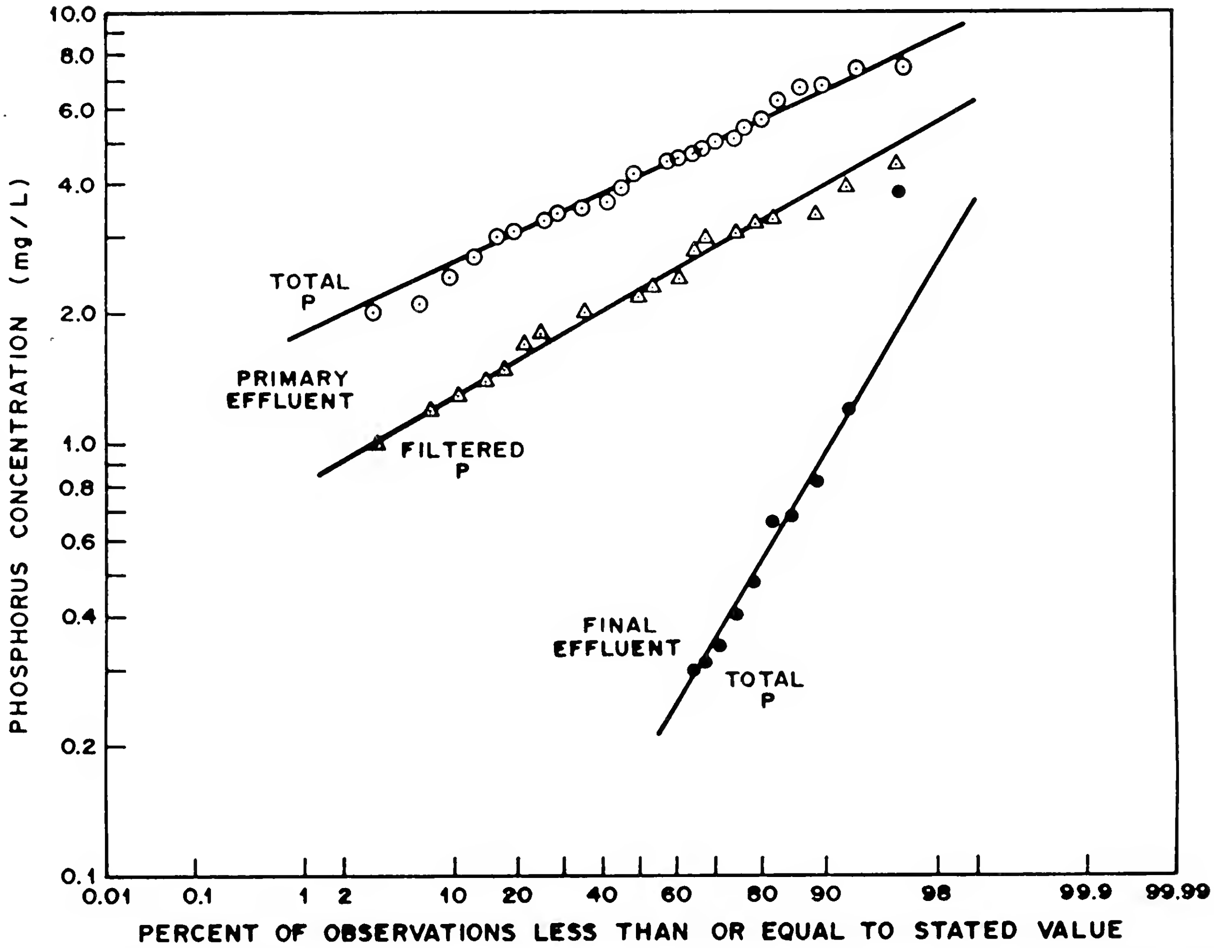


FIGURE: 3: FREQUENCY DISTRIBUTION OF PHOSPHORUS IN

during Phase 2. The high influent and primary effluent total phosphorus concentrations noted during Phase 2 (>15 mg/L) were absent from the Phase 3 data. The maximum primary effluent total phosphorus concentration recorded over the two-month period was 7.5 mg/L.

As shown in Table 6, the average effluent total phosphorus concentration over the two-month monitoring period was less than 0.5 mg/L, despite one serious plant upset and several less serious excursions in effluent TSS concentrations. The soluble phosphorus content of the final effluent never exceeded the analytical detection limit, typically 0.3 mg/L for the sample volume available. The overall average chemical dosage was 7.4 mg Al/L (Table 4) for all of Phase 3, which was comparable to the dosage applied during Phase 2 (8.1 mg Al/L). However, the molar metal to soluble phosphorus dosage (Al:P) ratio averaged 4.23 during Phase 3 compared to 0.94 during Phase 2 as a result of the dramatic reduction in influent phosphorus loading. Under these dosage conditions, virtually complete precipitation of phosphorus was achieved.

The Phase 3 program can be divided into two periods based on the alum dosage rate. From early in February until March 4, the chemical feedrate was maintained at the level that the plant had been using throughout most of 1986. On March 5, the chemical dosage rate was increased to determine if the effluent total phosphorus concentration could be maintained consistently at less than 0.5 mg/L. Data from these two operating periods are summarized in Table 7. The average for the high dosage period of March 5 to March 30 excludes the plant upset on March 31.

TABLE 7. COMPARISON OF LOW AND HIGH DOSAGE PERIODS

PERIOD	NO. OF DAYS OF DATA	AVERAGE FLOW (m^3/d)	ALUM DOSAGE		EFFLUENT QUALITY (mg/L)	
			mg/L	$\frac{\text{mol Al}}{\text{mol P}}$	TSS	TP
Feb 17-Mar 4	9	15,340	5.9	2.09	13.9	<0.49
Mar 5-Mar 30	16	18,080	8.8	5.25	11.2	<0.28

During the February 17 to March 4 period, the average alum dosage was 5.9 mg/L, equivalent to a molar Al:P ratio of 2.1. Under these dosage conditions, the average effluent total phosphorus content was less than 0.5 mg/L. The effluent total phosphorus concentration exceeded 0.5 mg/L on three occasions during this period. During the subsequent period, the alum dosage averaged 8.8 mg Al/L; however, the Al:P ratio at these dosage conditions exceeded 5 due to a lower soluble phosphorus content of the primary effluent. Despite higher hydraulic loading during the second operating period, effluent TSS concentrations were comparable and the effluent total phosphorus concentration averaged less than 0.28 mg/L. During this period, the effluent total phosphorus exceeded 0.50 mg/L on one occasion (6 percent of the time) and was typically at or near the analytical detection limit (0.3 mg/L).

Figure 4 presents a chronological plot of the alum dosage data during Phase 3. During February, the dosage was relatively constant in the 6 to 8 mg/L range. The aluminum content of the mixed liquor (mg Al/g TSS) was stable, indicative of equilibrium conditions in the system. At the beginning of March, there was considerable variability in the dosage due to high flows and chemical metering pump adjustment problems. Subsequently, the dosage stabilized in the 8 to 12 mg/L range. The aluminum content of the mixed liquor continued to increase over the final two weeks of monitoring, suggesting that equilibrium conditions had not been achieved at the SRT operating point.

2.4 Other Factors

2.4.1 Sludge Management Processes

The sludge management train at the Collingwood WPCP incorporates a flotation thickener for waste activated sludge (WAS) prior to two-stage anaerobic digestion of thickened WAS and raw primary sludge. The plant has traditionally operated with a high mixed liquor concentration in the aeration tanks, resulting in high SRTs and low organic loadings, because of an inability of the sludge management train to adequately handle the waste activated sludge produced. Under most circumstances, the high SRT does not adversely affect plant performance. However, under high flow conditions, clarifier washout can result because of the high sludge blankets maintained in the clarifiers and the inability to automatically increase recycle rates to compensate for the high clarifier loadings. In addition, operation at a

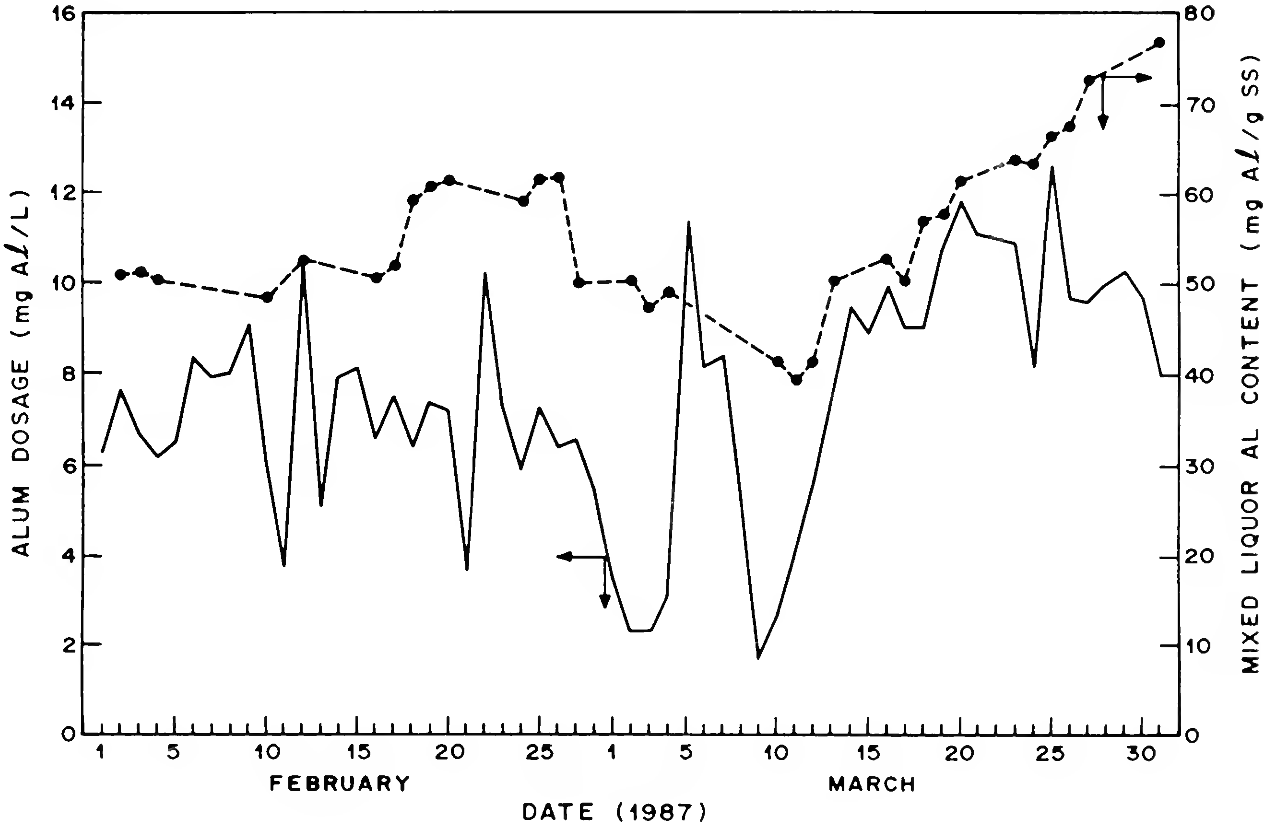


FIGURE 4: CHRONOLOGICAL PLOT OF DOSAGE DATA

high SRT results in nitrification in the plant and increased oxygen transfer requirements. Therefore, as part of Phase 3, the sludge management train was reviewed to identify process and hydraulic bottlenecks.

The bottleneck in the process is the flotation thickener. The 13.94 m^2 thickener was designed to handle approximately 210 L/min; however, plant staff have found that at flows in excess of approximately 100 L/min, process efficiency deteriorates significantly. Excessive turbulence and a low air-to-solids ratio results in poor solids capture in the unit. Mechanical modifications and experimentation with polymers have failed to increase throughput.

Operation at a lower SRT requires increased sludge waste rates which could be achieved by maintaining the present WAS feedrate to the DAF thickener and supplementing the wastage by directing an additional WAS flow to the primary clarifiers. At the present time, plant staff do not have the capability to waste sludge to the primary clarifiers rather than to the thickener. Modifications to allow this approach would result in operation at a lower SRT and reduce biomass inventory in the aeration tanks. Slightly lower raw sludge concentrations would result due to the presence of waste activated sludge; however, digestion capacity is adequate to handle the increased raw sludge volume anticipated.

An additional problem with the sludge handling train relates to inoperable flow metering equipment. Waste sludge volume is presently estimated based on mass balances around the dissolved air flotation thickener. Therefore, the calculated SRT is an estimate only at present.

2.4.2 Analytical Methodologies

Throughout the Phase 3 program, plant staff conducted phosphorus analyses on a routine basis on raw sewage, primary effluent and final effluent samples which were also analyzed by CANVIRO. Plant analyses were done using the stannous chloride method(4). CANVIRO analyses were done according to the vanadomolybdophosphoric acid method(4). Both laboratories analyzed filtered and unfiltered samples for total phosphorus, with sample digested according to the persulphate digestion method(4) at the Collingwood WPCP laboratory and by the sulphuric acid-nitric acid digestion method(4) at CANVIRO.

TABLE 8. COMPARISON OF PLANT (P) AND CANVIRO (C) ANALYTICAL RESULTS

TOTAL PHOSPHORUS						FILTERED PHOSPHORUS					
RAW SEWAGE		PRIMARY EFFLUENT		FINAL EFFLUENT		RAW SEWAGE		PRIMARY EFFLUENT		FINAL EFFLUENT	
P*	C*	P	C	P	C	P	C	P	C	P	C
7.5	4.6	7.0	6.8	0.30	0.40	5.0	2.9	1.5	4.4	0.24	<0.23
4.5	4.6	1.5	4.7	0.24	<0.23	1.3	3.5	4.5	3.1	0.45	<0.23
3.8	4.3	2.0	4.6	0.50	<0.23	2.5	3.2	0.5	3.4	0.10	<0.31
18.0	4.8	4.5	5.0	0.24	<0.24	12.5	3.1	1.3	3.1	0.20	<0.23
3.5	5.1	2.5	4.8	0.30	<0.23	0.02	4.9	0.003	3.2	0.01	<0.23
9.0	6.9	2.5	4.5	0.70	0.82	4.5	2.3	5.2	3.3	1.70	<0.26
9.5	5.2	2.0	3.5	2.10	1.20	3.0	3.5	3.5	3.4	1.20	<0.23
		8.5	6.3	1.40	0.34			4.0	2.0	2.10	<0.21
		13.2	5.7	3.00	0.68			8.5	3.0	0.70	<0.24
		6.0	3.5	1.30	0.48			5.3	1.8	0.90	<0.19
		11.0	7.5	1.00	0.30			2.3	2.0	0.80	<0.21
		5.5	3.4	1.20	0.24			7.5	1.5	1.20	<0.25
		7.0	3.3	1.80	<0.25			7.0	2.2	0.80	<0.21
		10.0	2.7	1.00	<0.30			5.0	3.9	1.40	<0.23
		9.0	3.3	1.60	<0.23			3.0	2.4	1.00	<0.21
		10.5	7.4	1.20	<0.23			2.0	2.4	0.70	<0.21
		8.0	5.4	1.80	<0.23			3.1	2.2	0.70	<0.21
		12.0	3.6	0.75	<0.23			3.0	2.8	0.50	<0.19
		9.5	4.5	0.60	0.28			1.8	2.0	0.50	<0.22
		6.2	4.5	1.50	0.24			3.0	2.2	0.60	<0.22
		4.5	3.6	1.80	0.66			1.6	1.7	0.30	<0.26
		11.2	3.1	0.60	<0.26			1.2	1.3	1.04	<0.24
		5.8	5.1	6.60	3.80						
		2.8	4.2								
AVERAGE 7.97	5.07	6.88	4.60	1.37	<0.53	4.12	3.34	3.40	2.60	0.78	<0.23

* P = Collingwood WPCP Lab results.
C = CANVIRO results.

Comparative results for various sample types are presented in Table 8. Plant results were found to be erratic and anomalies were identified between total phosphorus, total filtered phosphorus and suspended solids results. Plant results also significantly over-estimated the final effluent total phosphorus content compared to CANVIRO and limited MOE results.

Blind standards were submitted to both laboratories, with satisfactory results. A thorough analysis of the Collingwood plant methodology did not identify the specific cause of the discrepancy. The stannous chloride method is more sensitive than the vanadomolybdophosphoric acid method, giving a lower detection limit with a considerably smaller sample volume. It is also more rapid than the vanadomolybdophosphoric acid method, because it is not necessary to concentrate a large sample volume by evaporation prior to colour development. However, the stannous chloride method, because of its greater sensitivity, is also more sensitive to technician techniques[4].

2.4.3 Dosage Calculations

Miscalibration of the new chemical storage tank at the time of installation resulted in a consistent over-estimation of alum dosage whenever this tank was used as the feed source. The actual dosage when this tank was being used was 62.4 percent of the reported dosage.

2.5 Summary

The at-source control program initiated by industries contributing significant phosphorus loading to the Collingwood WPCP successfully reduced influent phosphorus concentrations experienced at the plant. As a result, the plant was able to achieve an effluent total phosphorus concentration of less than 1 mg/L without any increase in chemical dosage. Further, an effluent total phosphorus limit of 0.5 mg/L was shown to be achievable at the plant except during periods of peak flow and high suspended solids carryover from the secondary clarifier. Operation at a lower SRT (lower biomass inventory) would reduce problems with suspended solids carryover under these peak hydraulic loading conditions.

Problems with analyses for total phosphorus at the plant were identified. These problems make control of chemical dosage very difficult and over-estimate the actual effluent total phosphorus concentrations achieved by the plant.

3.0 DUFFIN CREEK WATER POLLUTION CONTROL PLANT

3.1 Background

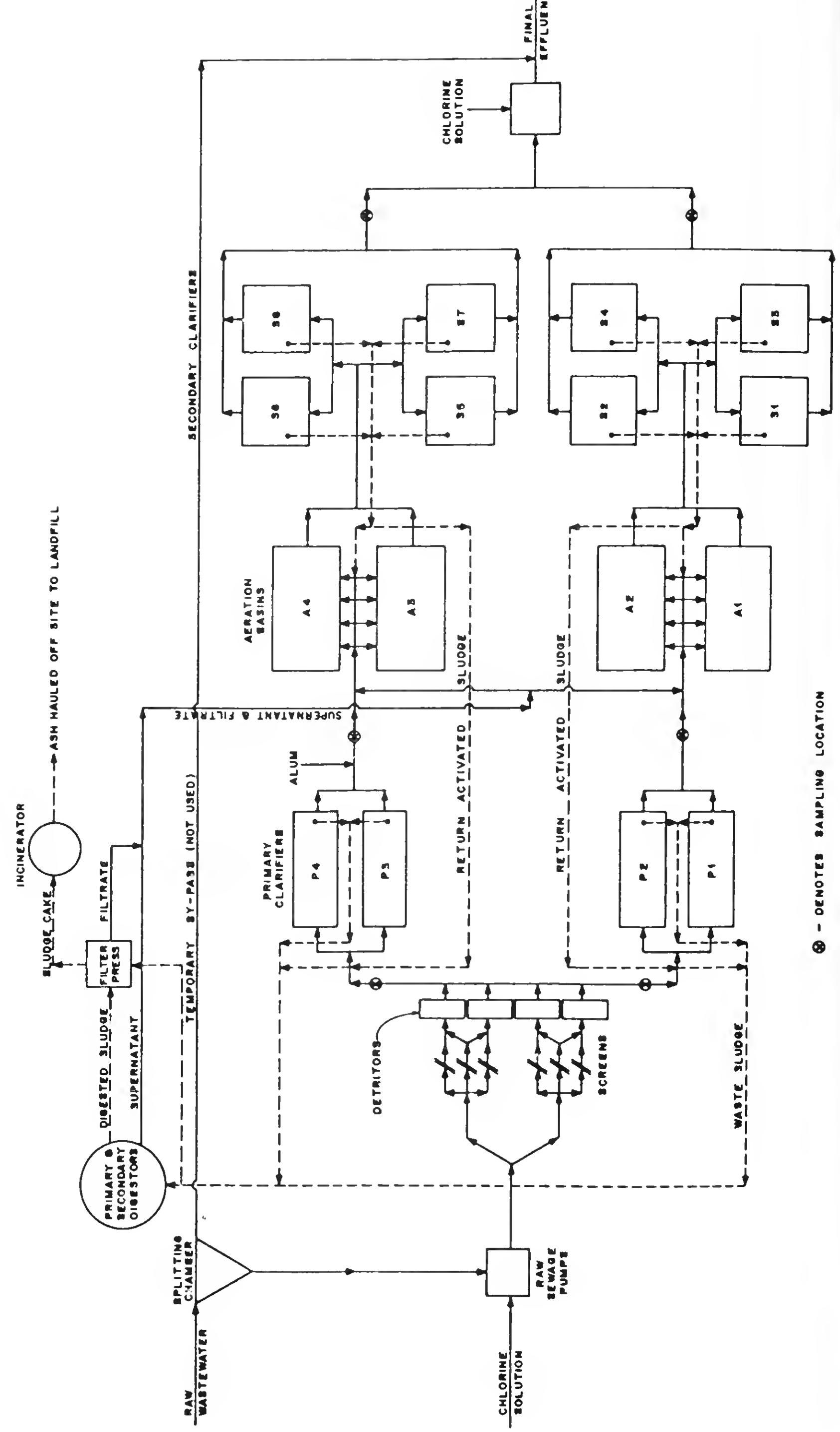
3.1.1 Plant Description

The Duffin Creek WPCP is a conventional activated sludge plant located in Pickering, near the mouth of the Duffin Creek. The plant, which is operated by the Regional Municipality of Durham, is the first stage in a four-stage facility which will eventually serve over 800,000 people connected to 112 km (70 mi.) of trunk sewer in the Regions of Durham and York. The completed first stage has an average daily flow capacity of 181,800 m^3/d (40.0 MIGPD). Figure 5 presents a schematic diagram of the plant. Key design information for the facility was presented in the Phase 2 report(2).

3.1.2 Historical Performance

Prior to September 25, 1986, alum was used for phosphorus removal. Alum was applied at two locations, in the effluents from the primary clarifiers and the aeration basins. About 10 to 20 percent of the total alum was added after primary clarification. The remainder (80 to 90 percent) was added to the aeration basins.

Table 9 provides a summary of the annual performance for the Duffin Creek WPCP for 1981 through 1985. The level of total phosphorus discharged in the effluent from the plant has typically been high. Average annual total phosphorus concentrations in the effluent have exceeded 1 mg/L for 3 of the last 5 years. The 5-year average effluent total phosphorus concentration was 1.30 mg/L. Total phosphorus levels in effluent from the Duffin Creek WPCP exceeded 1.0 mg/L for 12 of 24 months in 1984 and 1985 (50 percent). The highest monthly average effluent total phosphorus concentration was 1.4 mg/L, observed during 3 months in 1985 (January, April and June).



RAW WASTEWATER
SPLITTING CHAMBER
CHLORINE SOLUTION
RAW SEWAGE PUMPS
PRIMARY & SECONDARY DIGESTORS
DIGESTED SLUDGE
SUPERNATANT
FILTER PRESS
SLUDGE CAKE
INCINERATOR
ASH HAULED OFF SITE TO LANDFILL
FILTRATE
TEMPORARY BY-PASS (NOT USED)
SUPERNATANT & FILTRATE
SECONDARY CLARIFIERS
DETRITORS
SCREENS
WASTE SLUDGE
PRIMARY CLARIFIERS
P4
P3
P2
P1
ALUM
RETURN ACTIVATED SLUDGE
AERATION BASINS
A4
A3
A2
A1
S8
S7
S6
S5
S4
S3
S2
S1
CHLORINE SOLUTION
FINAL EFFLUENT
⊗ - DENOTES SAMPLING LOCATION

TABLE 9. ANNUAL AVERAGE PERFORMANCE OF DUFFIN CREEK WPCP

PARAMETER	YEAR					5 YEAR AVERAGE
	1981	1982	1983	1984	1985	1981-1985
Avg. Daily Flow ($1000\ m^3/d$)	41.37	84.51	95.12	121.13	149.87	97.53
BOD_5 - Influent (mg/L)	200.5	124.1	194.0	159.9	144.2	164.9
BOD_5 - Effluent (mg/L)	14.9	14.1	22.5	12.8	14.3	15.7
TSS - Influent (mg/L)	246.0	183.6	288.0	252.8	251.3	244.2
TSS - Effluent (mg/L)	18.0	12.2	25.2	15.9	15.9	17.1
Total P - Influent (mg/L)	7.00	7.01	8.08	7.19	6.05	7.08
Total P - Effluent (mg/L)	0.98	1.75	1.73	0.98	1.03	1.30

3.1.3 Performance During Phase 2

The Duffin Creek WPCP was selected for in-plant monitoring during Phase 2 and samples were collected on twelve days between August 5 and September 3, 1986. Table 10 presents a summary of plant operating data (including data collected by CANVIRO) for the month long sampling period. Table 11 presents a summary of results of the Phase 2 sampling program. Effluent quality, in terms of BOD_5 and TSS, appeared to be high in comparison to the historical data. Average total phosphorus levels in the secondary effluents exceeded 1.00 mg/L.

The average alum dose applied appears to have been low at 2.8 mg Al/L. However, a molar ratio of Al:P for the west side of the plant of 1.4:1 was adequate to achieve 75 percent reduction, based on literature values. As shown by the average soluble phosphorus concentrations in the primary and secondary effluents from the west plant, approximately 75 percent of the soluble phosphorus was removed. The molar ratio of Al:P for the east side of the plant was relatively low at 1.1:1, which was lower than the ratio required for 75 percent reduction (molar ratio 1.38:1). The average percent reduction in soluble phosphorus between the east primaries and secondaries was 67 percent, based on concentrations of 2.65 mg/L and 0.87 mg/L, respectively.

TABLE 10. SUMMARY OF DUFFIN CREEK OPERATING CONDITIONS (AUGUST 5 - SEPTEMBER 3, 1986)

PARAMETER		AVERAGE	MAXIMUM	MINIMUM
Flow (m^3/d)		186,900	291,870	154,420
MLSS (mg/L)	West(1)	3,801	9,320	2,055
	East(2)	2,958	7,840	1,064
MLVSS (%)	West	54.1	64	39
	East	52.7	66	35
RAS (mg/L)	West	7,359	19,810	3,260
	East	6,745	21,820	1,512
BOD_{in} (mg/L)	West(3)	81.9	119	52
	East(3)	75.8	132	44.6
F:M	West	0.19	0.30	0.15
	East	0.31	0.58	0.19
SVI (mL/g)	West	39.4	53	28
	East	36.3	46	26
SRT (d)	West	3.6	7.7	2.4
	East	2.9	6.7	2.0
Al Dose (mg/L)(4)		2.8	3.2	1.7

Notes: (1) Based on plant operating data for two west basins.
(2) Based on plant operating data for two east basins.
(3) Primary effluent total BOD_5.
(4) Average concentration of Al in alum = 43.4 g Al/L.

TABLE 11. SUMMARY OF PERFORMANCE MONITORING DATA FOR DUFFIN CREEK WPCP

STREAM		AVERAGE CONCENTRATIONS (mg/L)			
		BOD_5	TSS	TOTAL P	SOLUBLE P
Raw Sewage	West	92.4	222.7	6.24	2.60
	East	103.4	246.1	7.86	2.85
Primary Effluent	West	-	-	6.61	2.37
	East	-	-	6.26	2.65
Secondary Effluent	West	6.24	10.67	1.03	0.58
	East	6.28	13.42	1.50	0.87

3.1.4 Problem Identification

The Phase 2 monitoring program conducted at the Duffin Creek WPCP confirmed historical plant performance. Flows to the plant averaged 184,356 m^3/d during the monitoring period, representing an increase of about 25 percent over the average daily flow for 1985; the average flow observed during the sampling program was 98 percent of the design capacity.

Based on Phase 2 monitoring program results, it was determined that insufficient alum dosage was the principal factor contributing to inconsistent phosphorus levels in effluent from the Duffin Creek WPCP. As indicated by the results obtained, the ratio of aluminum to soluble phosphorus (in the primary effluent) was just equal to or less than that required for 75 percent removal of soluble phosphorus. It was postulated that increasing the alum dosage such that the molar ratio of Al:P was greater than 1.38:1, for both sides of the plant, the final effluent phosphorus concentration would be reduced to less than 1.00 mg/L.

3.2 Phase 3 Program

3.2.1 Approach

On September 25, 1986, the phosphorus removal chemical used at Duffin Creek was changed from alum to ferrous sulphate. The ferrous sulphate was initially used on a three-month trial to determine phosphorus removal effectiveness as well as other impacts on plant operations (for example, cost and sludge production). Table 12 presents a summary of plant performance for October, November and December 1986.

The average flow during the last quarter of 1986 was 186,162 m^3/d, which was slightly lower than the average flow for the Phase 2 monitoring period. Raw sewage quality during October, November and December was similar to that observed previously, although TSS appeared to be higher and total phosphorus appeared to be lower than usual. Secondary effluent, in terms of TSS, was consistent with typical plant performance.

TABLE 12. MONTHLY PLANT PERFORMANCE AFTER IMPLEMENTATION OF FERROUS SULPHATE ADDITION

PARAMETER		MONTH			OVERALL AVERAGE
		OCTOBER	NOVEMBER	DECEMBER	
Flow (m^3/d)		184,047	153,880	179,100	186,162
Raw Sewage					
TSS (mg/L)	West	212	370	361	318
	East	189	374	218	267
Total P (mg/L)	West	4.2	7.3	4.3	5.7
	East	3.9	6.7	2.9	4.8
Secondary Effluent					
TSS (mg/L)	West	23	12	10	14.8
	East	22	11	10	14.4
Total P (mg/L)	West	1.13	0.70	0.45	0.75
	East	1.55	0.53	0.40	0.81

Of particular interest was the significant reduction in secondary effluent total phosphorus concentrations between October and December. In October, total phosphorus levels averaged 1.13 mg/L and 1.55 mg/L for the west and east sides, respectively, which represented typical effluent concentrations. In December, however, the levels dropped to 0.45 mg/L and 0.40 mg/L for the west and east sides, respectively.

The average ferrous sulphate dosages for December were 10.3 mg Fe/L and 7.0 mg Fe/L, for the west and east plants, respectively. Based on the average primary effluent soluble phosphorus concentrations of 2.37 mg/L and 2.65 mg/L obtained during Phase 2 (see Table 11), the weight ratios of Fe:P were 4.35:1 and 2.64:1 for the west and east plants, respectively. These ratios are in excess of the stoichiometric ratio of 1:1 required to achieve 75 percent reduction in phosphorus levels. As indicated by the data shown in Table 12, the actual average phosphorus reductions were 90 percent and 86 percent, respectively. The results obtained for December support the general premise that given sufficient chemical dosage, adequate phosphorus removal can be achieved.

On the basis of the improved phosphorus removal effectiveness, lower cost, ready availability, as well as other factors, it was decided that ferrous sulphate would be used as the phosphorus removal chemical at Duffin Creek WPCP for 1987. Given that phosphorus concentrations in the effluent from Duffin Creek could be maintained below 1.0 mg/L, the Phase 3 monitoring program was instituted to examine the effective use and impacts of ferrous sulphate on the plant.

The specific objectives of the Phase 3 monitoring program were:

1. To optimize chemical dosage rates in order to achieve 1.0 mg/L or lower of phosphorus in plant effluent on a monthly basis.
2. To determine the significance of the difference in influent quality between the west and east sides of the plant.
3. To establish the quality of the chemical used for phosphorus removal.
4. To determine the loading of phosphorus to the primary clarifiers from digester supernatant and filter press filtrate.
5. To review solids retention and sludge generation rates.
6. To characterize the iron content of sludge prior to incineration.
7. To examine the long term effects of the use of iron salts on the fluidized bed incinerator and off-gas treatment and handling equipment.

3.2.3 Monitoring Program

The Duffin Creek WPCP was monitored for a period of approximately seven weeks from February 5 through March 27, 1987. Influent, primary and secondary effluents were sampled three times per week and each side of the plant was sampled separately. Twenty-four hour composite samples of raw sewage (downstream of the detritors) and primary effluent were collected. Twenty-four flow proportional composite samples of secondary effluent, prior to chlorination, were also collected.

A number of other samples were also collected, including dewatered sludge (prior to incineration), filter press filtrate, digester supernatant, ferrous sulphate and mixed liquor.

3.3 Phase 3 Results

3.3.1 Plant Operating Conditions

Table 13 presents a compilation of plant operating data, supported by data collected by CANVIRO, for the seven week sampling period at the Duffin Creek WPCP.

TABLE 13. SUMMARY OF DUFFIN CREEK OPERATING CONDITIONS (FEBRUARY 5 - MARCH 27, 1987)

PARAMETER		AVERAGE	MAXIMUM	MINIMUM
Flow (m^3/d)		174,154	449,670	149,610
MLSS (mg/L)	West(1)	3,925	5,009	2,826
	East(2)	3,022	4,665	1,221
MLVSS (%)	West	57	60	41
	East	61	68	42
RAS(3) (mg/L)	West	8,189	10,652	5,916
	East	3,643	5,612	2,016
BOD_{in} (mg/L)	West(4)	153	208	97
	East(4)	178	222	130
F/M	West	0.16	0.37	0.09
	East	0.17		
SVI	West	112	314	61
	East	144	333	82
Fe Dose (mg/L)	West	6.1	12.4	1.7
	East	6.3	13.1	1.7

Notes: (1) Based on plant operating data for two west basins.
(2) Based on plant operating data for two east basins.
(3) Data for February 1987 only.
(4) Primary effluent total BOD_5.

The average daily flow during this period was 174,154 m^3/d, equivalent to 91 percent of the design capacity. The average daily flow observed during the Phase 3 monitoring was approximately 7 percent lower than the average daily flow through the plant during Phase 2. The maximum flow observed during Phase 3 monitoring was 449,670 m^3/d, which was observed on March 2. All flows were less than the peak hydraulic capacity for the plant (473,125 m^3/d).

The characteristics of the biological systems observed during Phase 3 were different from those observed during Phase 2. Specifically, the MLSS and SVIs for both the west and east plants were higher during Phase 3 than Phase 2. The east plant appeared to be subject to significant fluctuations in terms of SVI. Return activated sludge solids concentrations for the east plant were lower and more variable than levels recorded for the west plant, which appeared to be operating in a more stable mode.

Ferrous sulphate was added to the wastewater on each side of the plant at a rate varying from 8 L/min up to 21 L/min. Based on ferrous sulphate samples collected during the monitoring period, as well as samples analyzed by the Region of Durham (at the Duffin Creek WPCP laboratory), an average iron content of 5.4 percent was calculated. The chemical dosage, as iron, averaged 6.1 mg Fe/L for the west plant and 6.3 mg Fe/L for the east plant. Ferrous sulphate dosages ranged from 1.7 mg Fe/L during high flow to 13.1 mg Fe/L.

In order to examine overall plant performance, data collected during the monitoring period was supplemented by plant operating records for January and April. Table 14 presents a summary of the influent, primary effluent and secondary effluent qualities for January through April 1987.

Raw sewage quality during the first four months of 1987 was comparable to Phase 2 influent quality, with the exception of BOD_5. The average BOD_5 concentrations during Phase 2 were 92.8 mg/L and 103.4 mg/L for the west and east plants, respectively. BOD_5 levels in the raw sewage entering the west and east plants during the January to April period were 150 mg/L and 147 mg/L, respectively. These concentrations represented increases of about 1.7 and 1.4 times the Phase 2 concentrations. The influent quality for January to April 1987 appears to be comparable to historical raw sewage quality.

TABLE 14. SUMMARY OF PERFORMANCE MONITORING DATA FOR DUFFIN CREEK WPCP

STREAM	AVERAGE CONCENTRATIONS (mg/L)			
	BOD_5	TSS	TOTAL P	SOLUBLE P
West				
Raw	156	241	5.91	-
Primary	-	-	4.42	1.33(3)
Secondary: flow-prop.(1)	-	-	0.33	0.26
composite (2)	22	14	0.48	0.24
East				
Raw	147	239	5.88	-
Primary	-	-	4.83	1.93(3)
Secondary: flow-prop.(1)	-	-	0.54	0.38
composite (2)	22	14	0.64	0.40

Notes:
(1) Results based on flow-proportioned samples collected during the Phase 3 monitoring period from February 5 to March 27, 1987.
(2) Results based on plant performance records for January, February, March and April 1987.
(3) Does not include results for January 1987.

Effluent quality, in terms of BOD_5 and TSS, during the first four months of 1987 was high in comparison to Phase 2 and historical effluent qualities. As shown in Table 14, average BOD_5 and TSS levels were 22 mg/L and 14 mg/L, respectively, for both the west and east plants.

Average phosphorus concentrations in the secondary effluents from both the west and east plants were lower than levels previously recorded. Comparison of the flow-proportional total phosphorus concentrations of 0.33 mg/L and 0.54 mg/L obtained during Phase 3 monitoring for the west and east plants are 68 percent and 64 percent lower than total phosphorus results obtained during Phase 2. Similar results were observed for flow-proportional soluble phosphorus levels, which decreased by 55 percent for the west plant and 56 percent for the east plant. Secondary effluent composite total phosphorus levels for the period from January to April 1987 were low in comparison to historical values. Figures 6 and 7 present probability distributions

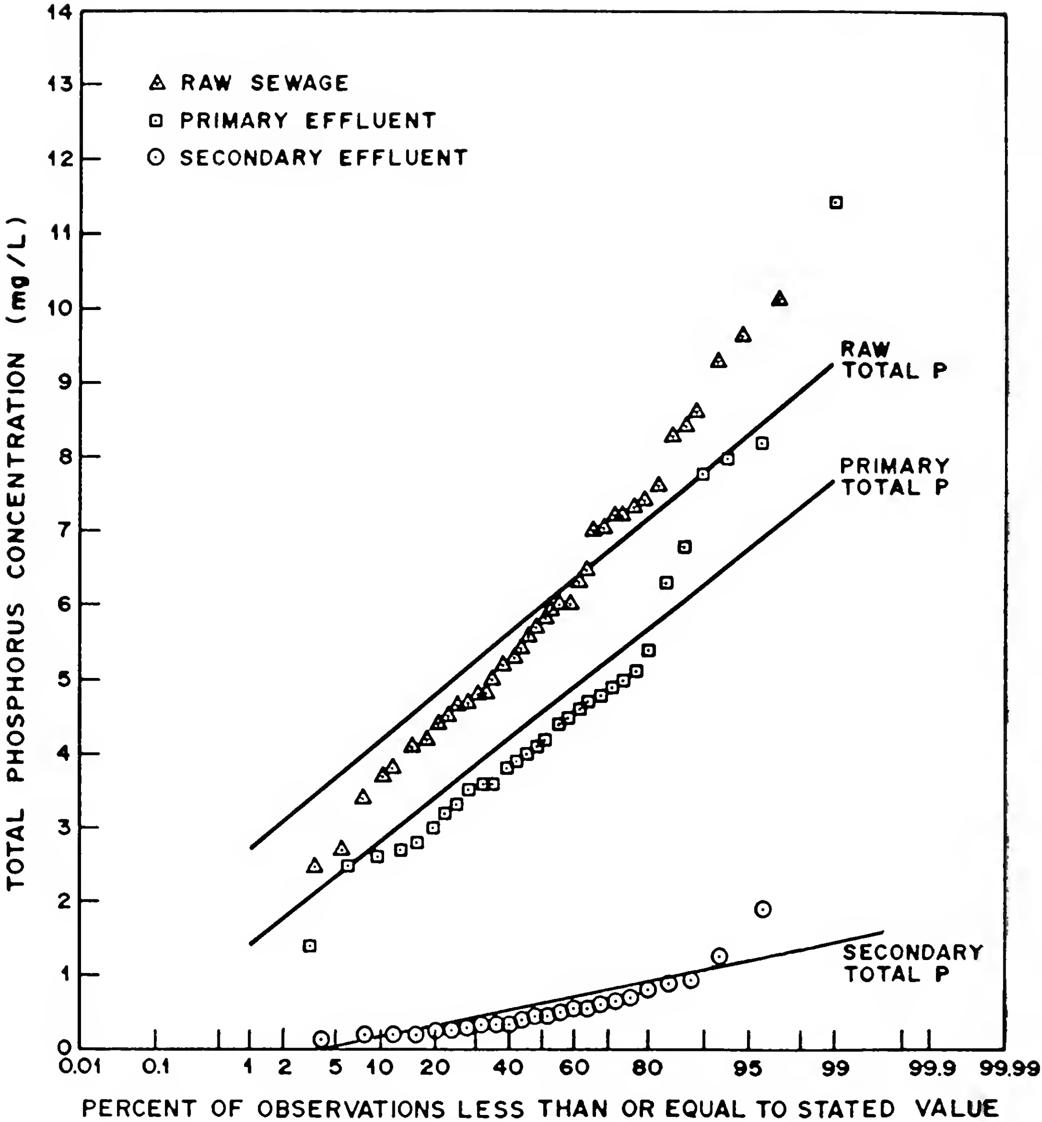


FIGURE 6 : DUFFIN CREEK WEST PLANT

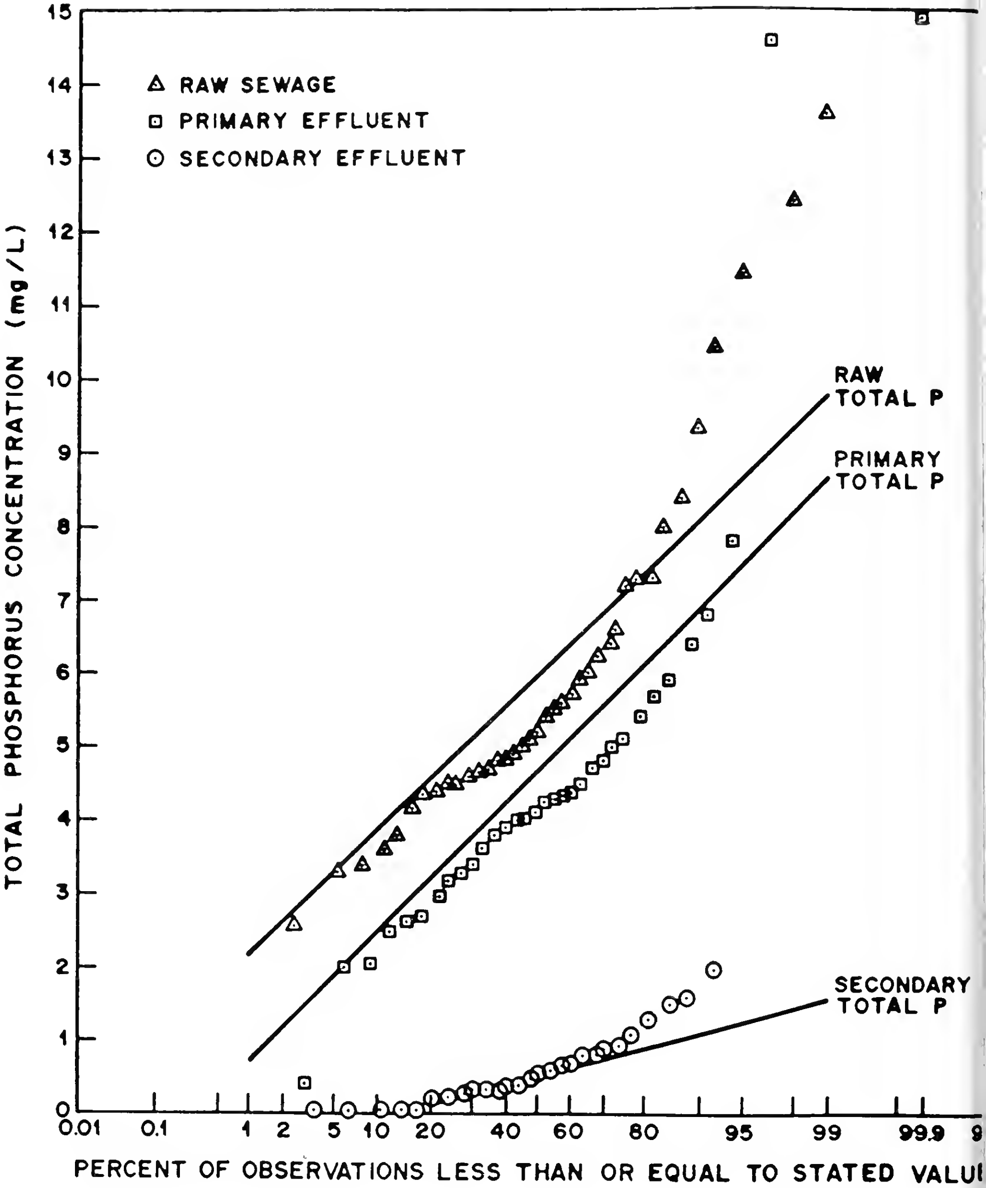


FIGURE 7 : DUFFIN CREEK EAST PLANT

for total phosphorus concentrations in the raw sewage, primary effluent and secondary effluent from the west and east sides of the Duffin Creek WPCP for the Phase 3 monitoring period.

Average total phosphorus removal in the west primaries was 25 percent and was 18 percent in the east primaries. It should be noted that these reductions represent removal mechanisms other than precipitation using ferrous sulphate. Chemical precipitation resulted in removal of 95 percent of total phosphorus and 80 percent of soluble phosphorus in secondary clarifiers on the west side of the plant. Total and soluble phosphorus removals for the east side of the plant, after chemical addition, were 89 percent and 80 percent, respectively, based on average results shown in Table 14 for composite samples of secondary effluent.

3.3.2 Phosphorus Removal Performance

Key operating parameters affecting phosphorus removal at the Duffin Creek WPCP are presented in Table 15.

The average iron dosages applied to the west and east plants were 5.9 mg Fe/L and 6.1 mg Fe/L, respectively. The average molar ratio of iron to phosphorus on the west side of the plant was 1.5; average weight ratio of Fe:P for the west plant was 2.7. The relatively low average primary effluent soluble phosphorus concentrations coupled with the high Fe:P ratio resulted in low secondary effluent phosphorus levels. The average total phosphorus concentration in the secondary effluent from the west plant was 0.40 mg/L, with average soluble and particulate fractions of approximately 47 percent and 53 percent, respectively.

The average molar ratio of Fe:P on the east side of the plant was 1.4. The average weight Fe:P ratio was 2.6. These ratios are not significantly different than those observed for the west plant. The average total phosphorus level in secondary effluent from the east plant was 0.60 mg/L, comprised of 0.36 mg/L soluble phosphorus and 0.24 mg/L particulate phosphorus.

The results obtained from the west and east plants, in terms of molar ratio of Fe:P and secondary effluent total phosphorus, appear to indicate that a molar ratio of 1.5 (Fe:P) would be sufficient to reduce the effluent total phosphorus concentrations to below the guideline level (1.0 mg/L) on a consistent basis.

TABLE 15. SUMMARY OF KEY OPERATING PARAMETERS AFFECTING PHOSPHORUS REMOVAL AT DUFFIN CREEK WPCP

DATE	AVERAGE FLOW (m^3/d)	WEST								EAST							
		IRON DOSE (mg/L)	PRIMARY SOL. P (mg/L)	Fe:P RATIO		EFFLUENT QUALITY (mg/L)				IRON DOSE (mg/L)	PRIMARY SOL. P (mg/L)	Fe:P RATIO		EFFLUENT QUALITY (mg/L)			
				Wt.	Mol.	TSS	Tot.P	Sol.P	Part.P			Wt.	Mol.	TSS	Tot.P	Sol.P	Part.P
Feb 6	157,640	-	2.55	-	-	4	0.20	0.20	0.00	-	2.65	-	-	10	1.50	1.00	0.50
9	163,100	7.9	1.80	4.4	2.4	10	0.40	0.30	0.10	7.9	2.05	3.9	2.1	7	2.00	2.00	0.00
11	159,670	8.3	2.65	3.1	1.7	8	0.20	0.10	0.10	9.2	2.70	3.4	1.9	11	0.20	0.08	0.12
13	157,100	11.2	1.60	7.0	3.9	10	0.40	0.10	0.30	13.1	3.00	4.4	2.4	22	0.70	0.20	0.50
16	156,890	6.9	3.00	2.3	1.3	8	0.20	0.00	0.20	6.9	2.50	2.8	1.5	16	0.60	0.45	0.15
18	153,720	6.7	2.64	2.5	1.4	10	0.80	0.60	0.20	6.7	2.70	2.5	1.4	11	1.30	1.20	0.10
20	156,090	6.3	2.30	2.7	1.5	8	0.30	0.20	0.10	6.3	2.55	2.5	1.4	11	0.30	0.13	0.17
23	154,130	6.4	2.33	2.7	1.5	13	0.45	0.15	0.30	6.4	2.10	3.0	1.7	9	0.15	0.08	0.07
25	153,470	3.2	1.65	1.9	1.1	9	0.19	0.15	0.04	3.2	2.25	1.4	0.8	8	0.11	0.04	0.07
27	149,690	6.4	1.95	3.3	1.8	8	0.40	0.20	0.20	6.4	1.88	3.4	1.9	10	0.40	0.20	0.20
Mar 2	449,670	1.7	1.90	0.9	0.5	20	0.96	0.20	0.76	1.7	2.10	0.8	0.4	16	0.93	0.20	0.73
4	169,910	4.6	2.00	2.3	1.3	9	0.15	0.04	0.11	5.4	2.40	2.3	1.2	14	0.50	0.15	0.35
6	231,480	3.5	2.80	1.3	0.7	10	0.24	0.05	0.19	4.4	1.60	2.8	1.5	14	0.52	0.24	0.28
9	203,390	4.5	-	-	-	15	0.66	0.28	0.38	5.3	-	-	-	17	0.84	0.37	0.47
11	181,040	5.0	3.70	1.4	0.8	12	0.46	0.09	0.37	4.5	3.20	1.4	0.8	12	0.80	0.23	0.57
13	180,280	5.9	-	-	-	8	0.30	0.15	0.15	5.9	3.00	2.0	1.1	16	0.80	0.30	0.50
16	169,940	6.4	2.50	2.6	1.4	9	0.55	0.45	0.10	6.4	2.20	2.9	1.6	16	0.08	0.05	0.03
18	149,610	6.7	-	-	-	10	0.90	0.30	0.60	5.3	3.00	1.8	1.0	4	0.30	0.30	0.00
20	163,290	5.1	-	-	-	9	0.20	0.10	0.10	5.5	2.00	2.8	1.5	5	0.20	0.10	0.10
23	168,370	5.9	-	-	-	4	0.33	0.20	0.13	5.9	3.64	1.6	0.9	4	0.33	0.26	0.07
27	168,880	5.8	-	-	-	9	0.20	0.05	0.15	5.8	1.60	3.6	2.0	5	0.05	0.05	0.00
Average	180,827	5.9	2.36	2.7	1.5	9	0.40	0.19	0.21	6.1	2.46	2.6	1.4	11	0.60	0.36	0.24

In order to examine the impact of changing the application point on phosphorus removal, the location of the ferrous sulphate feed line on the east side of the plant was relocated from the effluent channel feeding mixed liquor into the secondary clarifiers to the aeration tank, beginning March 16.

The average iron dosage to the east plant from March 16 to 27 was 5.6 mg Fe/L and the average primary effluent soluble phosphorus level was 2.48 mg/L. The average molar and weight Fe:P ratios during this period were 2.5 and 1.4, respectively. Average secondary effluent total and soluble phosphorus concentrations were 0.19 mg/L and 0.15 mg/L, respectively. These results tend to show that the addition of ferrous sulphate directly into the aeration basins improves phosphorus removal relative to injection into the aeration effluent channels; however, with results for only five days, there are too few data to support a definite conclusion regarding application point. There would seem to be no advantage to adding ferrous to the mixed liquor upstream of the clarifiers compared to adding ferrous to the aeration tank. The higher dissolved oxygen concentrations in the aeration tank will ensure complete oxidation of ferrous iron to ferric.

3.4 Other Considerations

With the implementation of ferrous sulphate for phosphorus removal at the Duffin Creek WPCP, a number of additional factors related to phosphorus removal were investigated to determine both short and long term impacts on the plant.

3.4.1 Ferrous Sulphate Quality

During the Phase 3 monitoring program samples of ferrous sulphate were collected for analysis of iron content as well as the presence and concentration of other metals. Table 16 presents the quality of the ferrous sulphate used at Duffin Creek WPCP from February 5 to March 27, 1986.

The average iron content of the ferrous sulphate was 5.91 percent and ranged from a low of 2.7 percent up to 7.9 percent. On the basis of the average daily flow for the Phase 3 monitoring period of 174,154 m^3/d and average application rate of 13 L/min, an average dose of 6.3 mg Fe/L was calculated. Average concentrations of other metals ranges from <0.6 mg/L for cadmium to 72.8 mg/L for chromium.

TABLE 16. FERROUS SULPHATE QUALITY

SAMPLE DATE	CONCENTRATION (mg/L)								
	CADMIUM	COBALT	CHROMIUM	COPPER	IRON	MOLYBDENUM	NICKEL	LEAD	ZINC
Feb 5/6	<1	<1	55	15	79,000	14	32	<2	80
10/11	<1	<1	40	11	75,000	<1	19	<2	50
13	<0.5	4.0	30	5.5	68,000	7	18	5	70
18	<0.5	5.0	98	13	60,000	25	54	5	10
24	<0.5	5.3	75	3.7	28,000	25	38	12	27
25	<0.05	3.8	69	10	27,000	21	30	8.2	130
Mar 3	<0.5	3.32	71	6.72	56,000	27.8	52.4	12.4	12.3
4	<0.5	4.04	100	10.2	49,400	29.0	63.6	15.0	41.8
10	<0.5	3.81	84.4	8.76	60,000	26.9	63.9	14.7	62.1
12	<0.5	3.62	97.6	9.27	68,500	27.4	63.0	4.94	34.9
16	<0.05	2.95	85.5	7.53	63,500	21.1	58.7	4.95	27.5
19	<0.05	2.65	65.5	6.05	61,000	14.2	33.8	6.15	15.8
24	<1.5	4.38	74.3	6.40	70,000	22.1	42.0	6.43	17.4
27	<1.5	3.45	74.0	5.45	62,000	20.1	52.0	5.15	27.8
Average	<0.6	3.45	72.8	8.47	59,100	20.1	44.3	7.42	43.3
Maximum	<1.5	5.3	100	15	79,000	29.0	63.9	15.0	130
Minimum	<0.05	<1	30	3.7	27,000	21	18	<2	10

Typical removal effectiveness via the activated sludge process for six of the metals in Table 16 are presented in Table 17[5]. Based on the average application rate of 13 L/min and the removal effectiveness shown, the theoretical daily metal sludge generation rates were calculated.

TABLE 17. MASS LOADING AND METAL SLUDGE GENERATION

METAL	AERATION TANK LOADING(1) (kg/d)	RANGE OF REMOVAL(2) (%)	SLUDGE GENERATION (kg/d)
Cadmium	0.01	0 - 99	>0 - 0.1
Chromium	1.36	5 - 99	0.01 - 1.29
Copper	0.16	2 - >99	>0 - 0.16
Lead	0.14	0 - >99	>0 - 0.14
Nickel	0.83	0 - >99	>0 - 0.83
Zinc	0.81	0 - 94	0.05 - 0.81

Notes: (1) Calculated using average ferrous sulphate application rate of 13 L/min and average concentrations shown in Table 16.

(2) Taken from U.S. EPA Treatability Manual, Vol.1 (1983).

The metal component of sludge handled at Duffin Creek WPCP could range from 0.06 kg/d (at minimum metal removal during aeration) to 3.24 kg/d (at maximum removal), based on the calculations presented in Table 17. Based on an average sludge generation rate of approximately 40,000 kg/d for the Duffin Creek WPCP, the total additional metal concentration of these six metals attributable to ferrous sulphate addition would be in the range from 1.5 mg/kg to 80 mg/kg.

A number of ferrous sulphate samples were also analyzed for acidity. The average acidity of six ferrous sulphate samples was 156,503 mg/L (as $CaCO_3$) and ranged from 137,690 mg/L up to 167,480 mg/L.

3.4.2 Sludge Generation

In order to examine the potential impact of ferrous sulphate use on sludge production at Duffin Creek WPCP, daily sludge flows for April 1987 were compared to those recorded for April 1986 when alum was used for phosphorus removal. Table 18 presents daily total solids generation rates, taken

TABLE 18. COMPARISON OF DAILY SOLIDS PRODUCTION FOR APRIL 1986 AND 1987

DAY	TOTAL SLUDGE SOLIDS PRODUCED (kg/d)	
	APRIL 1986	APRIL 1987
1	36,896	29,108
2	37,975	30,984
3	35,069	52,347
4	32,023	45,941
5	34,404	27,214
6	27,154	64,699
7	29,017	44,605
8	44,122	45,477
9	41,988	46,696
10	39,586	38,526
11	31,709	42,257
12	30,877	43,257
13	31,907	53,790
14	32,868	45,482
15	39,367	41,792
16	41,021	52,328
17	38,902	36,233
18	35,192	26,774
19	33,475	24,030
20	32,303	44,471
21	34,798	38,698
22	39,390	21,130
23	36,670	44,484
24	42,278	43,024
25	34,751	35,890
26	33,794	33,628
27	27,189	36,125
28	30,953	30,801
29	35,389	32,995
30	35,519	34,189
Average	35,220	39,566
Maximum	44,122	64,699
Minimum	27,154	21,130

from plant operating records. Raw sewage quality for these two time periods (BOD_5, TSS and total phosphorus) were not significantly different.

The average daily solids generation rate for April 1986 was 35,220 kg/d. This increased by approximately 12 percent, to 39,566 kg/d, in April 1987. The average daily flow for April 1986 was approximately 160,000 m^3/d compared to an average flow of 200,000 m^3/d for April 1987. Thus, sludge generation rates per m^3 of wastewater treated were approximately 0.22 kg/m^3 in 1986 when alum was being used for phosphorus removal at a dosage of approximately 4 mg Al/L compared to 0.20 kg/m^3 in 1987 when ferrous sulphate was being used for phosphorus removal at a dosage of approximately 6 mg Fe/L. The use of ferrous sulphate did not significantly impact on the sludge generation at the plant because the higher metal dosage of iron applied relative to aluminum was compensated by the lower sludge generation rate associated with iron salts(6).

3.4.3 Digester Supernatant and Filter Press Filtrate Quality

As shown in Figure 5, digester supernatant and filter press filtrate are returned to the plant at the head end of the aeration basins. In order to examine the impact of these streams on phosphorus removal, samples of both supernatant and filtrate were collected and analyses performed to determine total suspended solids and soluble phosphorus concentrations. Table 19 presents the TSS and soluble phosphorus levels in the samples collected.

For the data shown in Table 19, contributions of soluble phosphorus from either supernatant or filtrate would not likely have a significant impact on overall aeration tank concentrations, given that the flowrates of each stream are low in comparison to flow through the plant. The same could be said about suspended solids loading from the filtrate stream. TSS levels in digester supernatant are high, averaging 2.2 percent in the samples collected. Based on an estimated supernatant flow of 200 m^3/d, the supernatant solids would contribute approximately 20 mg/L to the influent concentration. The data do not suggest any significant resolubilization of precipitated phosphorus under anaerobic conditions in the digesters.

TABLE 19. CONCENTRATIONS OF TSS AND SOLUBLE PHOSPHORUS IN DIGESTER SUPERNATANT AND FILTER PRESS FILTRATE

DATE	DIGESTER SUPERNATANT		FILTRATE	
	TSS (mg/L)	SOLUBLE P (mg/L)	TSS (mg/L)	SOLUBLE P (mg/L)
Feb 6	-	-	80	5.3
10	16,375	12.1	86	5.6
11	-	-	-	6.3
12	22,540	6.4	-	-
17	16,700	5.2	-	-
19	30,700	9.4	-	-
23	24,300	7.4	41	5.2
24	-	-	43	4.8
25	-	8.3	-	-
26	-	-	40	2.8
Mar 3	-	-	34	2.1
5	-	-	22	3.8
Average	22,105	8.1	49	4.5

3.4.4 Sludge Quality

Samples of pressed sludge cake were collected prior to incineration in order to determine average iron content. As a comparison to iron levels in dewatered sludge cake at Duffin Creek WPCP, samples were also collected from Lakeview WPCP, which has been using iron for phosphorus removal for a number of years. Table 20 presents the iron and solids contents of sludge cakes collected from both Duffin Creek and Lakeview WPCPs.

TABLE 20. DEWATERED SLUDGE CAKE QUALITY COMPARISON

SAMPLE NO.	DUFFIN CREEK		LAKEVIEW	
	IRON (%)	TOTAL SOLIDS (%)	IRON (%)	TOTAL SOLIDS (%)
1	2.4	-	2.5	44.3
2	2.4	28.9	2.6	48.5
3	2.0	31.0	2.6	47.2
4	2.6	28.7	2.6	48.4
5	2.4	29.6	2.6	48.0
6	2.1	30.0	-	-
7	2.8	32.5	-	-
8	2.4	29.6	-	-
Average	2.4	30.0	2.6	47.3

The average iron content in dewatered sludge from Duffin Creek WPCP was 2.4 percent, which is comparable to that for Lakeview WPCP (2.6 percent). The difference in solids content between the sludge cakes from the two plants is due to the difference in sludge handling processes. At the Lakeview WPCP, sludges are thermally conditioned prior to dewatering.

3.4.5 Impact of Ferrous Sulphate on Sludge Treatment

Duffin Creek WPCP employs fluid bed incinerators for processing dewatered sludge. The residual ash is hauled to a sanitary landfill site while the incinerator off-gases are processed through a scrubber tower prior to discharge to the atmosphere.

Ferrous sulphate may impact the incineration/waste recovery system at Duffin Creek in two locations. In the fluidized bed, formation of slag, or clinkers, may ultimately lead to bed seizure. In the scrubber tower, salt build-up may result in acid formation which can lead to corrosion of metal components.

For the most part, fluidized beds have a relatively constant temperature throughout, with the exception of pockets of cooler air. Ferrous sulphate, or any metallic salt, typically has a melting point below the 860°C operating temperature of the incineration. As a result, the salts tend to melt, forming slag. When the slag cools, as it may at any location within the bed at which a temperature differential exists, a clinker is formed. Problems arise when clinker formation within the bed is allowed to progress uncontrolled, usually leading to seizure of the bed. To alleviate bed seizure, additives can be used, or bed tapping frequency can be increased. Tapping usually decreases the salt content of the bed as well. It should be noted that clinker formation is not a long term problem. In general, clinkers form within a few days to a week, such that consistent bed tapping should eliminate the cumulative effect of clinker formation.

Salt build-up in the scrubber tower is also influenced, indirectly, by bed tapping. The build-up of salt, with subsequent acid formation, appears to be of particular significance when chloride salts are involved; almost all the chlorine is converted to hydrochloric acid. In the case of sulphate, the problem is less clear, since most of the sulphate is converted to sulphur dioxide (which is non-soluble, and hence, not a problem). The

fraction converted to sulphite may result in formation of sulphuric acid. Salt build-up results from the carryover of ash (containing the salts) into the scrubbers. If the fluidized bed is tapped, however, ash carryover can be reduced with the subsequent reduction in associated salt carryover.

3.4.6 Comparison of Influent Quality of West and East Plants

The quality of the raw sewage influent to the west and east sides of Duffin Creek WPCP appears to be consistently different. In order to determine whether or not the difference in influent quality was statistically significant, raw sewage total suspended solids concentrations for February through December 1986 were analyzed. A paired Student's-t' test was conducted to determine the statistical significance of the difference. Based on results from this analysis, the difference in raw sewage influent to the west and east plants is not statistically significant at the 5 percent level. In addition, no significant difference could be identified based on analysis of phosphorus data for the east and west sides of the plant.

3.4.7 Cost Impacts

Use of alum at the Duffin Creek WPCP in 1986 cost approximately $550,000, based on alum costs of $180/tonne dry alum. Utilization of ferrous sulphate in 1987 will result in no cost (chemical and shipping free of charge). Historically, ferrous chloride and ferrous sulphate costs have been in the range of $0.45/kg Fe. Even under these circumstances, annual chemical costs for phosphorus removal at Duffin Creek would be only $180,000 based on use of ferrous sulphate. Thus, the plant has been able to achieve the effluent guideline for phosphorus by changing chemical from alum to ferrous sulphate and the improved performance has been achieved with a substantial operating cost savings.

3.5 Summary

The Phase 2 monitoring program at Duffin Creek WPCP identified insufficient dosage as the principal cause of inadequate phosphorus removal at the plant. Phosphorus removal chemical was subsequently changed from alum to ferrous sulphate in September 1986. Due to the lower chemical cost, the

chemical dosage was increased such that the Fe:soluble P (in the primary effluent) was sufficiently high to reduce effluent phosphorus levels to below the guideline level of 1 mg/L on a consistent basis. The plant effluent exceeded 1 mg/L on only one occasion during February and March 1987. The improvement in effluent quality was achieved at a substantial reduction in chemical costs to the plant.

4.0 TORONTO MAIN WPCP

4.1 Background

4.1.1 Plant Description

The Main WPCP is the largest of two major secondary treatment facilities serving Metropolitan Toronto. The facility is a conventional activated sludge plant designed to handle an average daily flow of 818,300 m^3/d (180 MIGPD) with a peak hydraulic flow of 1,638,000 m^3/d (360 MIGPD). A schematic flowsheet of the plant is provided in Figure 8. Key design parameters for the facility were presented in the Phase 2 report[2]. Phosphorus removal at the Main WPCP is achieved by ferrous chloride addition to the individual aeration tanks upstream of the overflow weirs to the secondary clarifiers.

4.1.2 Historical Performance

Table 21 summarizes the annual performance of the Main WPCP for the years 1981 to 1985. Effluent quality showed a deteriorating trend over this time period, despite minimal changes in plant hydraulic loadings. The most dramatic change in effluent quality was reflected by the increase in effluent TSS concentration from 12 mg/L to 26 mg/L between 1984 and 1985. Phosphorus removal performance during 1984 and 1985 was inconsistent. The plant achieved an annual average effluent total phosphorus concentration of less than 1 mg/L in 1984 and exceeded 1 mg/L by less than 10 percent in 1985; however, on a monthly basis, effluent total phosphorus exceeded 1 mg/L during 11 months in 1984 and 1985 (46 percent of the time). Based on monthly average data, the high effluent phosphorus levels in 1985 seemed to correlate to high effluent suspended solids concentrations.

4.1.3 Phase 2 Performance

The Main WPCP was monitored for a one month period between August 6 and September 2, 1986. During this period, unusually heavy precipitation resulted in average daily flows of 1,262,000 m^3/d or 154 percent of plant design. As a direct result of the high hydraulic loading, effluent quality during Phase 2 was poor, particularly in terms of suspended solids and total phosphorus. These results were not considered to be representative of normal plant operating conditions.

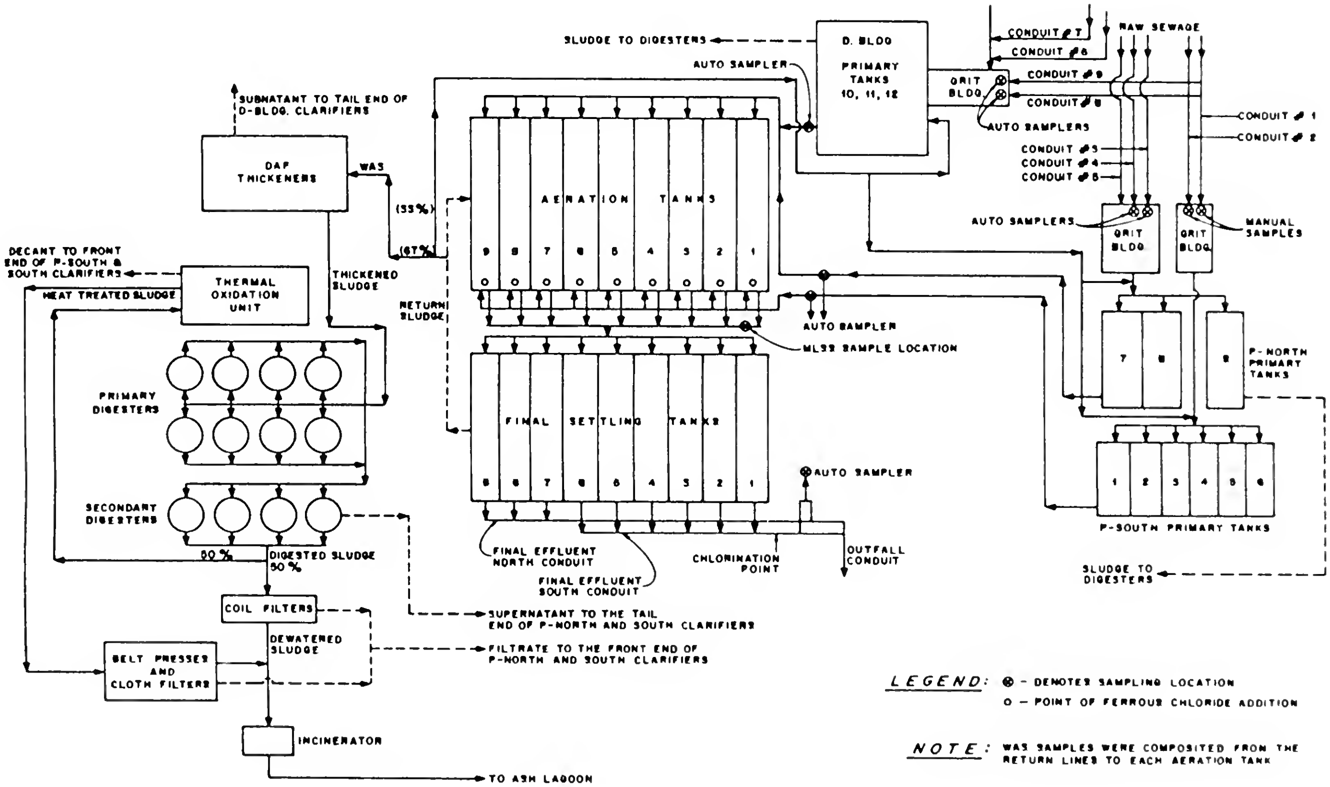


FIGURE 8 : SCHEMATIC FLOWSHEET OF TORONTO MAIN WPCP

TABLE 21. ANNUAL AVERAGE PERFORMANCE OF MAIN WPCP

PARAMETER	YEAR					5 YEAR AVERAGE 1981-1985
	1981	1982	1983	1984	1985	
Avg. Daily Flow ($1000\ m^3/d$)	752.36	709.18	737.59	677.25	683.83	712.04
BOD_5 - Influent (mg/L)	197.8	206.8	224.0	215.4	167.0	202.2
BOD_5 - Effluent (mg/L)	7.1	11.6	13.2	19.3	22.3	14.7
TSS - Influent (mg/L)	204.3	227.9	260.0	228.3	195.7	233.2
TSS - Effluent (mg/L)	11.7	13.9	11.8	11.9	26.0	15.1
Total P - Influent (mg/L)	5.80	6.40	5.93	5.88	5.85	5.97
Total P - Effluent (mg/L)	0.80	0.91	0.89	0.97	1.09	0.93

4.2 Phase 3 Program

4.2.1 Approach

The cause of the inconsistent performance of the Main WPCP, in terms of phosphorus removal, could not be established based on the Phase 2 results. Therefore, a thorough review of the historical plant operating and performance data was initiated in order to define specific causes of phosphorus removal inadequacies and to assess the feasibility of improving phosphorus removal performance by the low capital cost approaches which were within the scope of this investigation. Plant operating data for 1984 and 1985 were reviewed, focussing on key parameters related to phosphorus removal performance.

4.2.2 Results of Historical Data Analysis

Probability distributions of raw sewage flow and final effluent quality, in terms of suspended solids concentrations and total and soluble phosphorus concentrations, for 1984 and 1985 are presented in Figures 9, 10, 11 and 12, respectively, based on Main plant data. In addition, the probability distribution for the particulate phosphorus content of the final effluent was developed based on the difference between the total and filterable phosphorus concentrations and this distribution is shown in Figure 13. Chemical dosage data, expressed in terms of the molar metal (Fe) to soluble phosphorus ratio, is shown in Figure 14. Key results of these data analyses are summarized in Table 22.

There was no statistically significant difference (95 percent confidence) between the average daily flows at the Main WPCP in 1984 and 1985. In both years, design flow (818,300 m^3/d) was exceeded about 15 percent of the time. Despite the comparable hydraulic loadings on the plant, effluent quality was poorer in 1985 than in 1984 based on suspended solids concentration. The effluent guideline of 25 mg/L TSS was exceeded 25 percent of the time in 1985 compared to only 6 percent of the time in 1984. The similarity in the frequency distributions of influent flow between 1984 and 1985 suggests that the higher efluent suspended solids concentrations experienced in 1985 were not directly related to hydraulic loading conditions.

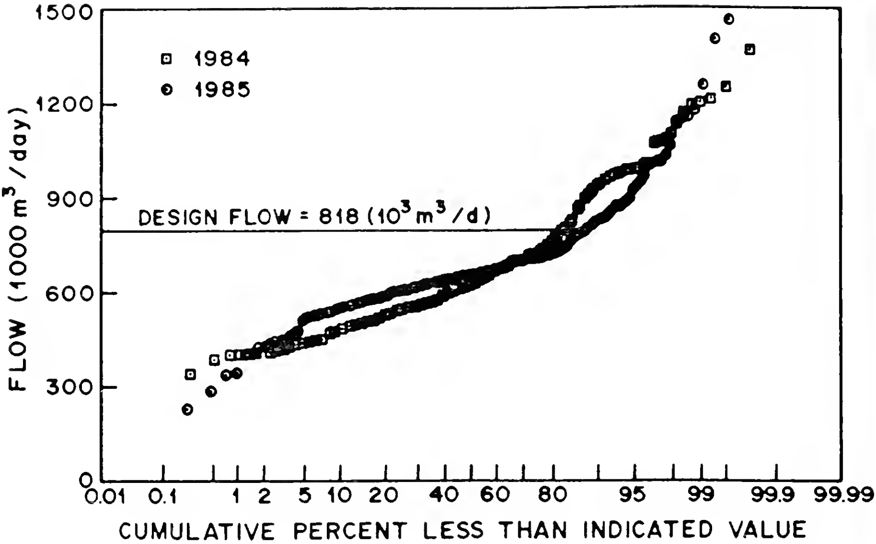


FIGURE 9 : PROBABILITY DISTRIBUTIONS OF MAIN WPCP DAILY FLOWS

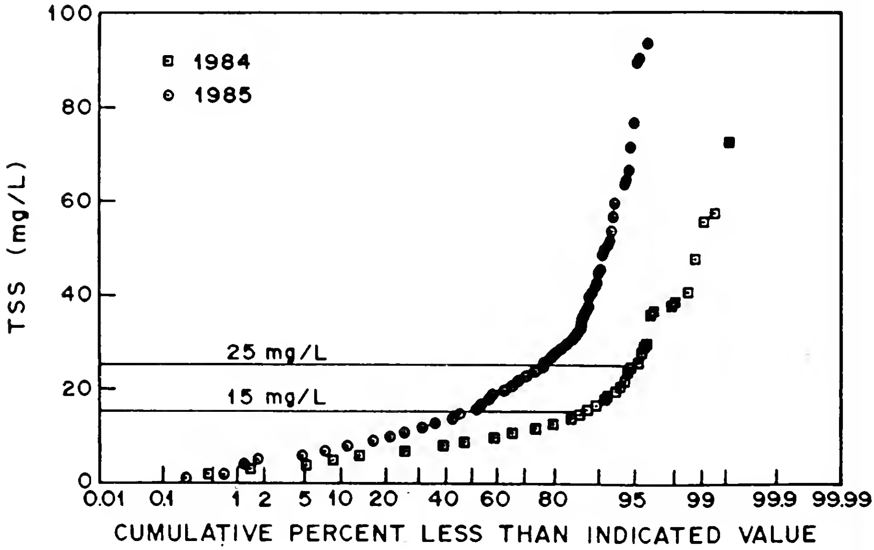


FIGURE 10 : PROBABILITY DISTRIBUTIONS OF MAIN WPCP EFFLUENT TSS CONCENTRATIONS

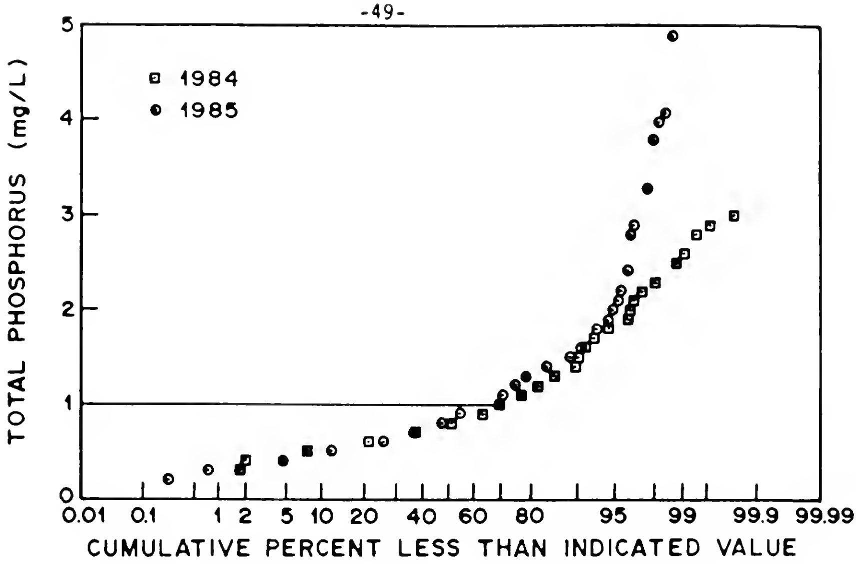


FIGURE 11: PROBABILITY DISTRIBUTIONS OF MAIN WPCP EFFLUENT TP CONCENTRATIONS

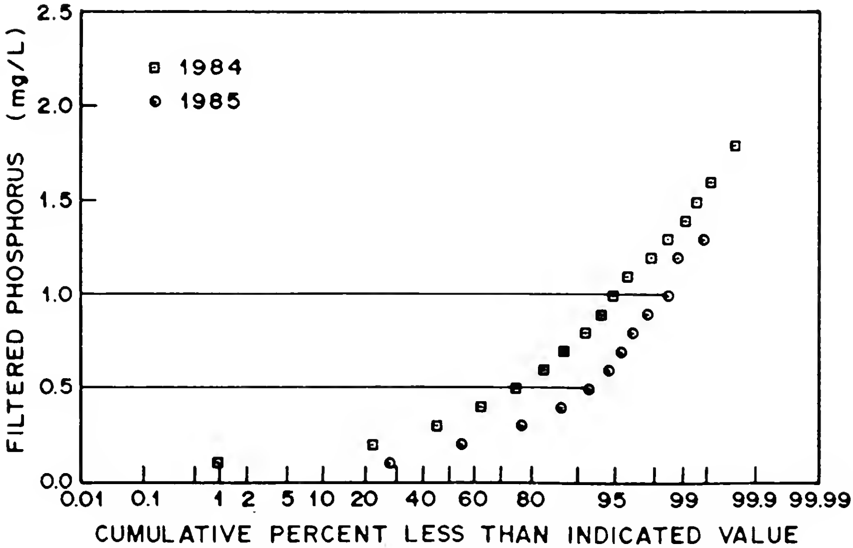


FIGURE 12: PROBABILITY DISTRIBUTIONS OF MAIN WPCP EFFLUENT FILTERED P CONCENTRATIONS

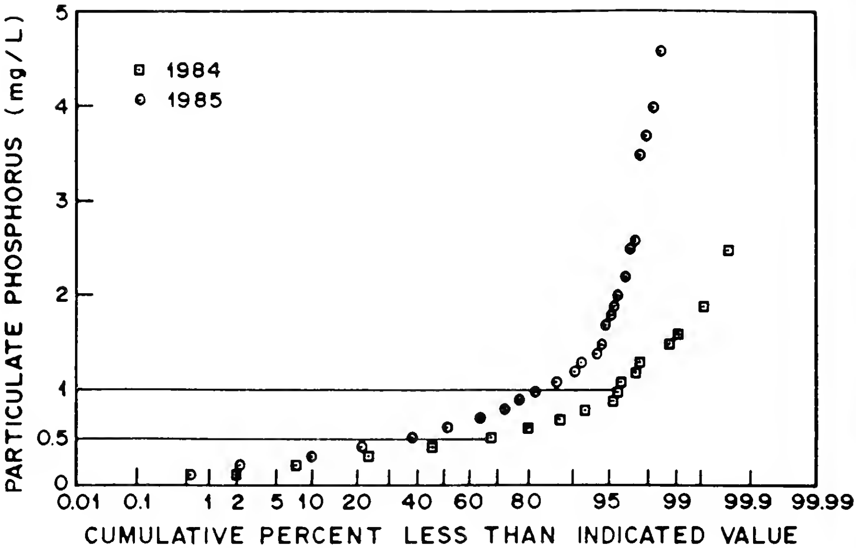


FIGURE 13 : PROBABILITY DISTRIBUTIONS OF MAIN WPCP EFFLUENT PARTICULATE P

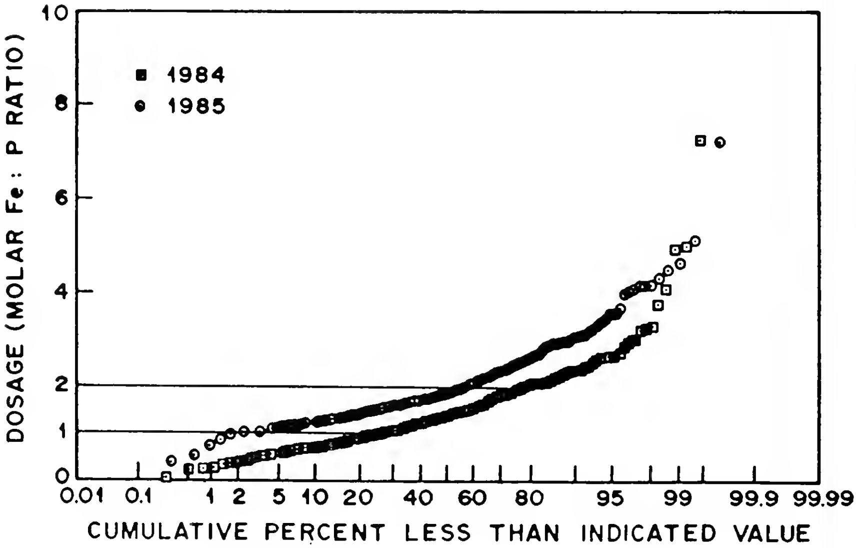


FIGURE 14 : PROBABILITY DISTRIBUTIONS OF MAIN WPCP CHEMICAL DOSAGE

TABLE 22. SUMMARY OF HISTORICAL DATA ANALYSIS FOR MAIN WPCP

PARAMETER	PROBABILITIES (Pr)			MEDIAN (50% of Observations Less than Value)		90 PERCENTILE (90% of Observations Less than Value)	
		1985	1985	1984	1985	1984	1985
Average Daily Flow (10^3 m^3/d)	Pr(Flow > Design)	17%	13%	650	620	940	830
TSS (mg/L)	Pr(TSS > 15 mg/L) Pr(TSS >25 mg/L)	15% 6%	55% 25%	10	14	19	50
Total Phosphorus (TP) (mg/L)	Pr(TP > 1 mg/L)	30%	39%	0.8	0.8	1.6	1.6
Soluble Phosphorus (SP) (mg/L)	Pr(SP > 1 mg/L) Pr(SP > 0.5 mg/L)	5% 25%	1% 8%	0.3	0.2	0.8	0.4
Particulate Phosphorus (PP) (mg/L)	Pr(PP > 1 mg/L) Pr(PP > 0.5 mg/L)	4% 39%	15% 59%	0.4	0.6	0.8	1.2
Molar Dosage (MD) (Fe:Influent SP)	Pr(MD > 1) Pr(MD > 2)	75% 18%	98% 42%	1.6	1.8	2.3	3.0

Based on the frequency distributions of 1984 and 1985 effluent total phosphorus concentration data (Figure 11), effluent quality was similar for 95 percent of the time in these years. Total phosphorus concentrations of less than 1 mg/L were achieved approximately 65 percent of the time in both years. However, the 1985 performance data indicate periods of very poor effluent quality (total phosphorus concentrations of 2 to 5 mg/L) compared to the 1984 performance data. These high effluent total phosphorus concentrations correspond to periods of elevated effluent suspended solids concentrations (50 to 100 mg/L). Effluent soluble phosphorus concentrations were lower in 1985 than in 1984 as shown in Figure 12. Soluble phosphorus concentrations exceeded 0.5 mg/L almost 25 percent of the time in 1984 compared to 8 percent of the time in 1985. The improvement in phosphorus precipitation in 1985 compared to 1984 was a result of increased chemical dosage from a level of 7.6 mg Fe/L (1984) to 8.8 mg Fe/L (1985). The molar metal to phosphorus ratio (Fe:P) increased significantly in 1985 compared to 1984 and exceeded 2.0 almost 40 percent of the time in 1985. Despite this increase in chemical dosage, total phosphorus removal performance deteriorated. This deterioration was a direct result of the increase in the particulate phosphorus in the effluent associated with the effluent suspended solids. In 1985, the particulate phosphorus content of the effluent alone exceeded 1.0 mg/L approximately 15 percent of the time. The increase in chemical dosage in 1985 was not sufficient to compensate for the deterioration in effluent quality related to suspended solids losses from the system.

Chronological plots of flow, effluent suspended solids and effluent total phosphorus data were generated to identify trends and correlations. To minimize day-to-day variability and facilitate data analysis and trend identification, seven-day moving averages were used. These chronological plots are presented in Figure 15 and Figure 16 for 1984 and 1985, respectively. Flows in excess of the design capacity of 818,300 m^3/d were experienced for two extended periods in 1984 (Feb/Mar and Apr/May) and four extended periods in 1985 (February, March, April and November). During these peak hydraulic periods, elevated effluent suspended solids concentrations were evident, along with elevated effluent total phosphorus concentrations. In 1985, there were two extended periods of time (June and September/October) when high effluent suspended solids concentrations were evident, along with high effluent total phosphorus concentrations, but flows were consistently lower than the design level.

Chronological plots (seven-day moving averages) of effluent total phosphorus, filtered phosphorus and chemical dosage (molar Fe:P ratio) are presented in Figures 17 (1984) and 18 (1985). Chemical dosage was highly variable in 1984, ranging from approximately 0.5 to more than 3.0. Peaks in the soluble phosphorus concentration in February, May, August and December 1984 coincided with periods of low chemical dosage. In 1985, as evident from the frequency distribution presented in Figure 13, chemical dosages increased to levels ranging from 1.2 to more than 3.0. This increase in dosage resulted in soluble phosphorus levels which never exceeded 1.0 mg/L and peaked over 0.5 mg/L on only three occasions. As noted, the improvement in phosphorus precipitation efficiency did not translate into an improvement in effluent quality in 1985 relative to 1984 because increases in the levels of particulate phosphorus in the effluent exceeded the decrease in the levels of soluble phosphorus.

Figure 19 presents chronological data for flows, effluent suspended solids and aeration tank mixed liquor concentrations at the Main WPCP for 1985. These data indicate that the elevated effluent suspended solids concentrations in June and September/October which could not be correlated to periods of high flow, correspond to periods of high mixed liquor concentrations in the aeration section of the plant (MLSS >5000 mg/L). The data suggest that performance problems during these two periods in 1985 were related to sludge management problems at the plant. Inability to control the biomass inventory at the plant by intentional wasting resulted in excessively high mixed liquor concentrations and, ultimately, the excess solids in the system were discharged in the plant effluent. Sludge settleability during these periods was not impaired (SVI 40-100) and biological process upset did not appear to be contributing to the poor effluent quality.

4.2.3 Problem Identification

During both 1984 and 1985, the Main WPCP experienced high hydraulic loading conditions for extended periods of time in the early spring and fall. During these periods, elevated effluent suspended solids concentrations resulted in non-compliance with the total phosphorus guideline of 1 mg/L. These events occurred about 15 percent of the time during both years.

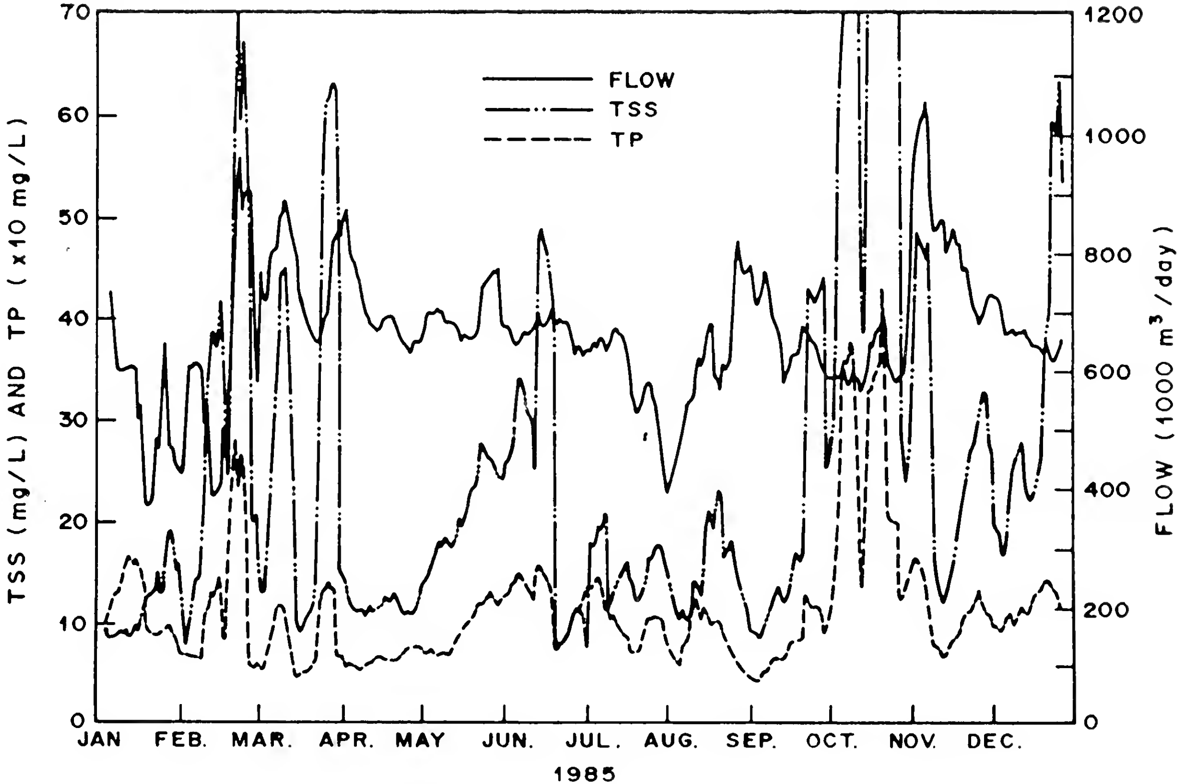


FIGURE 16 : CHRONOLOGICAL FLOW, TSS AND TP DATA
MAIN WPCP — 1985

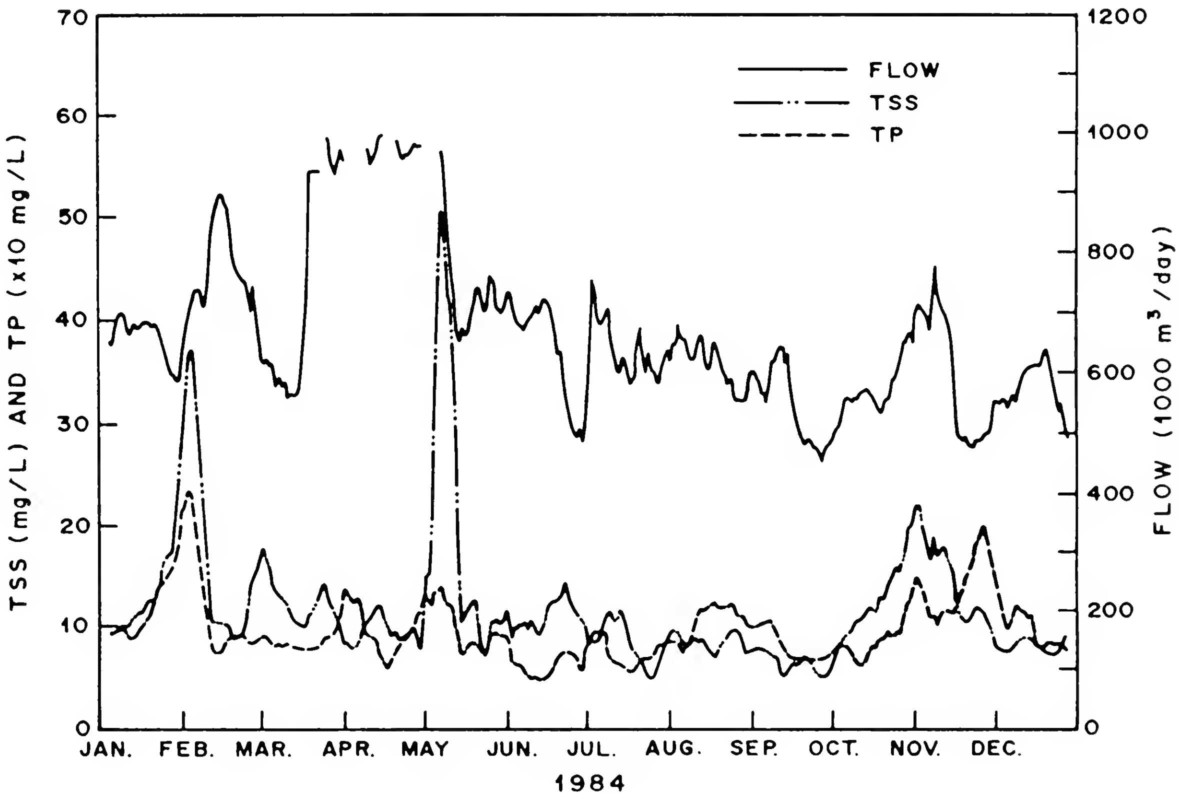


FIGURE 15 : CHRONOLOGICAL FLOW, TSS AND TP DATA MAIN WPCP – 1984

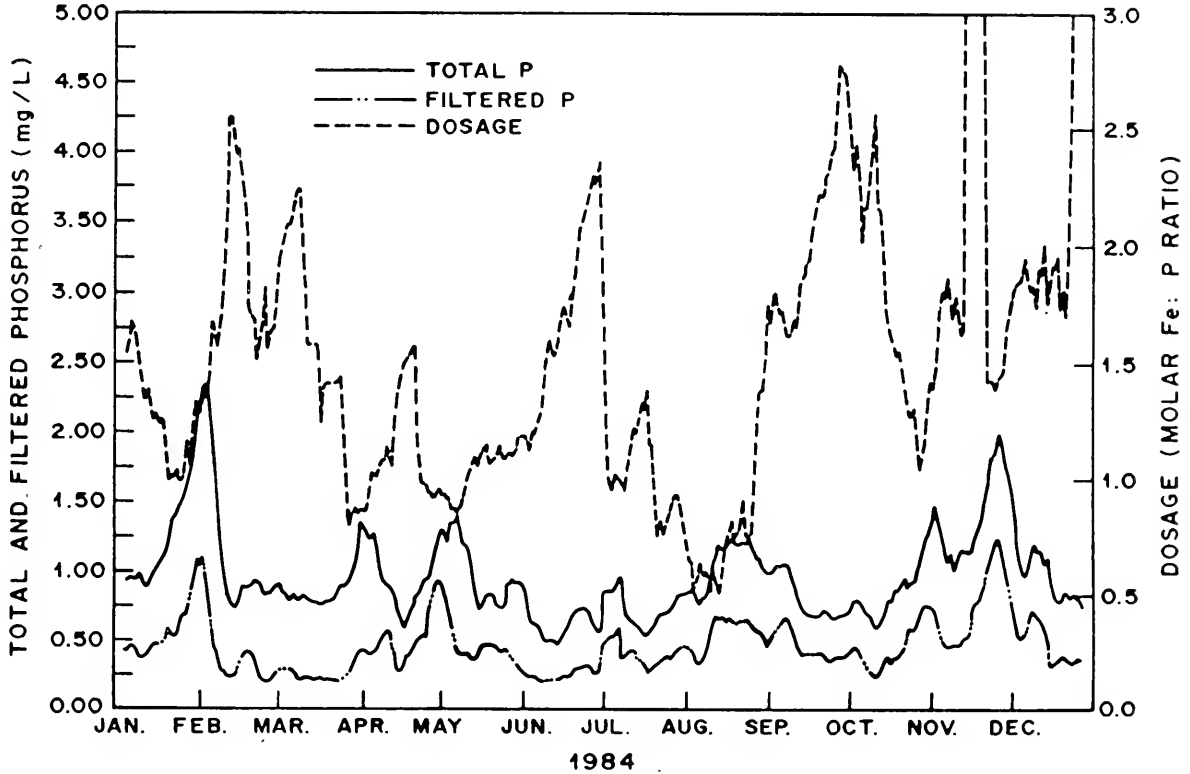


FIGURE 17 : CHRONOLOGICAL TP, SOLUBLE P AND DOSAGE DATA
MAIN WPCP — 1984

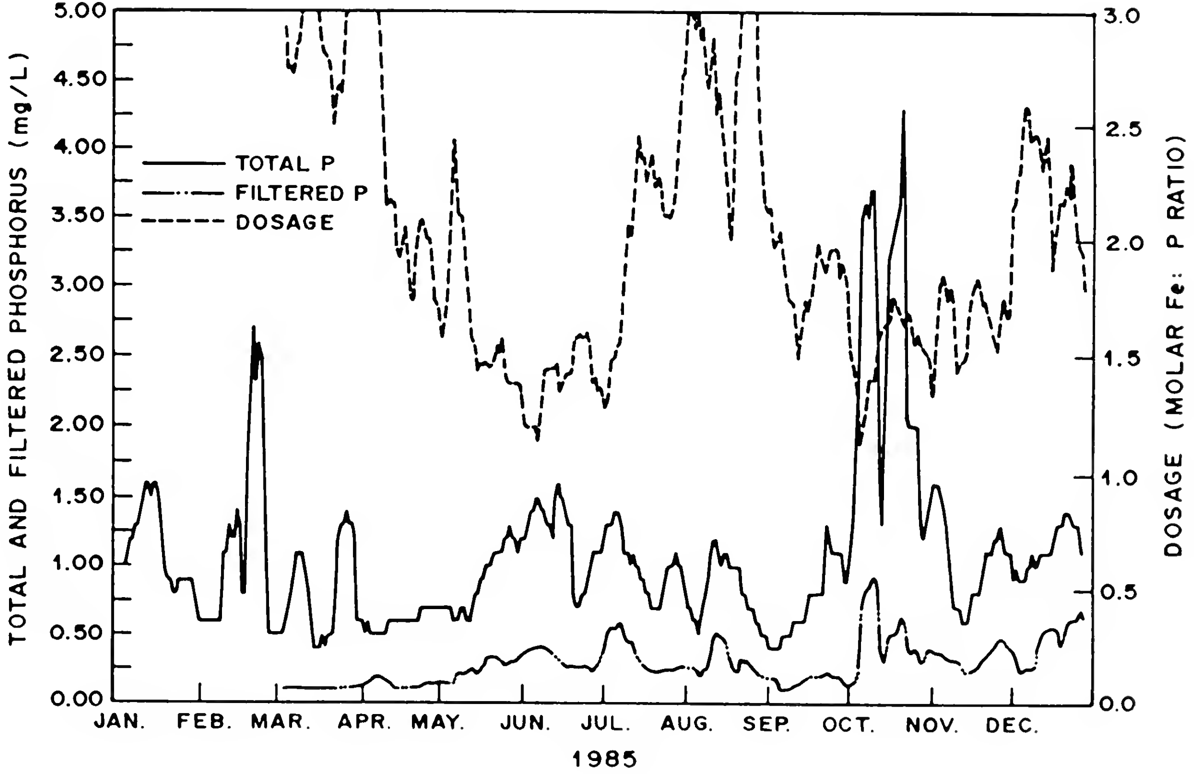


FIGURE 1.8 : CHRONOLOGICAL TP, SOLUBLE P AND DOSAGE DATA
MAIN WPCP — 1985

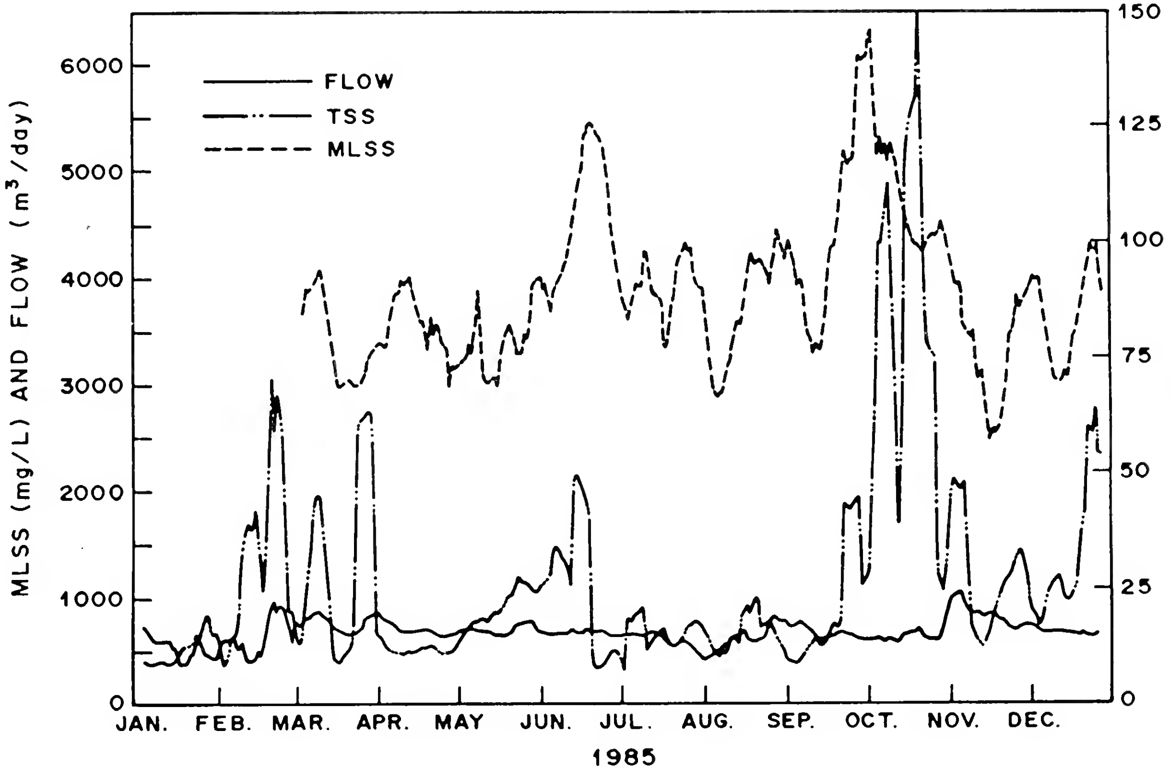


FIGURE 19 : CHRONOLOGICAL FLOW, MLSS AND TSS DATA MAIN WPCP — 1985

In 1985, increased chemical dosage rates were applied which effectively reduced the effluent soluble phosphorus concentration relative to 1984. Despite this improvement, effluent quality deteriorated in 1985 relative to 1984 because of sludge management problems at the plant. These sludge management problems were related to a combination of start-up, design and operational problems with the sludge handling system at the Main WPCP.

The sludge handling train at the Main WPCP was designed to incorporate waste activated sludge (WAS) thickening and anaerobic digestion, thermal conditioning of combined raw sludge and digested WAS with anaerobic treatment of 'heat-treat' liquor and dewatering and incineration of sludge cake. The design concept is illustrated schematically in Figure 20. Components of this system have been brought on-line since December 1981 when the thermal conditioning unit was commissioned. The belt presses went into operation in February 1984. To-date, plant staff have been unable to operate the sludge handling train as designed due to a variety of problems. The present operating mode is illustrated schematically in Figure 21. Operation in this mode has resulted in process bottlenecks which have limited the system ability to adequately handle the sludge generated at the plant.

At the present time, all sludge (thickened WAS and raw sludge) is being digested because of odour problems related to dewatering of thermally-conditioned, undigested raw sludge. Because the digestion system was intended to handle only WAS, it is overloaded. Supernatant quality is poor which results in an additional solids load on the process. Furthermore, it was intended to utilize existing digesters for the 'heat-treat' liquor pretreatment process. This concentrated liquor is presently returned to the plant untreated which applies an additional organic load on the system, further increasing solids generation in the biological process. Corrosion problems in the thermal conditioning decant tanks has limited system throughput. In addition, serious mechanical problems with the belt presses necessitated their removal and repair. As a result, existing coil filters and drum filters have been brought on-line for sludge dewatering. Sludge dewatered on the coil filters does not undergo thermal conditioning and, due to its higher moisture content, can be handled in only selected multiple hearth incinerators. Conveyor system design also produces a serious bottleneck in the incinerator feed because only some dewatering equipment and some incinerators can be operated at one time. The start-up problems with the belt presses

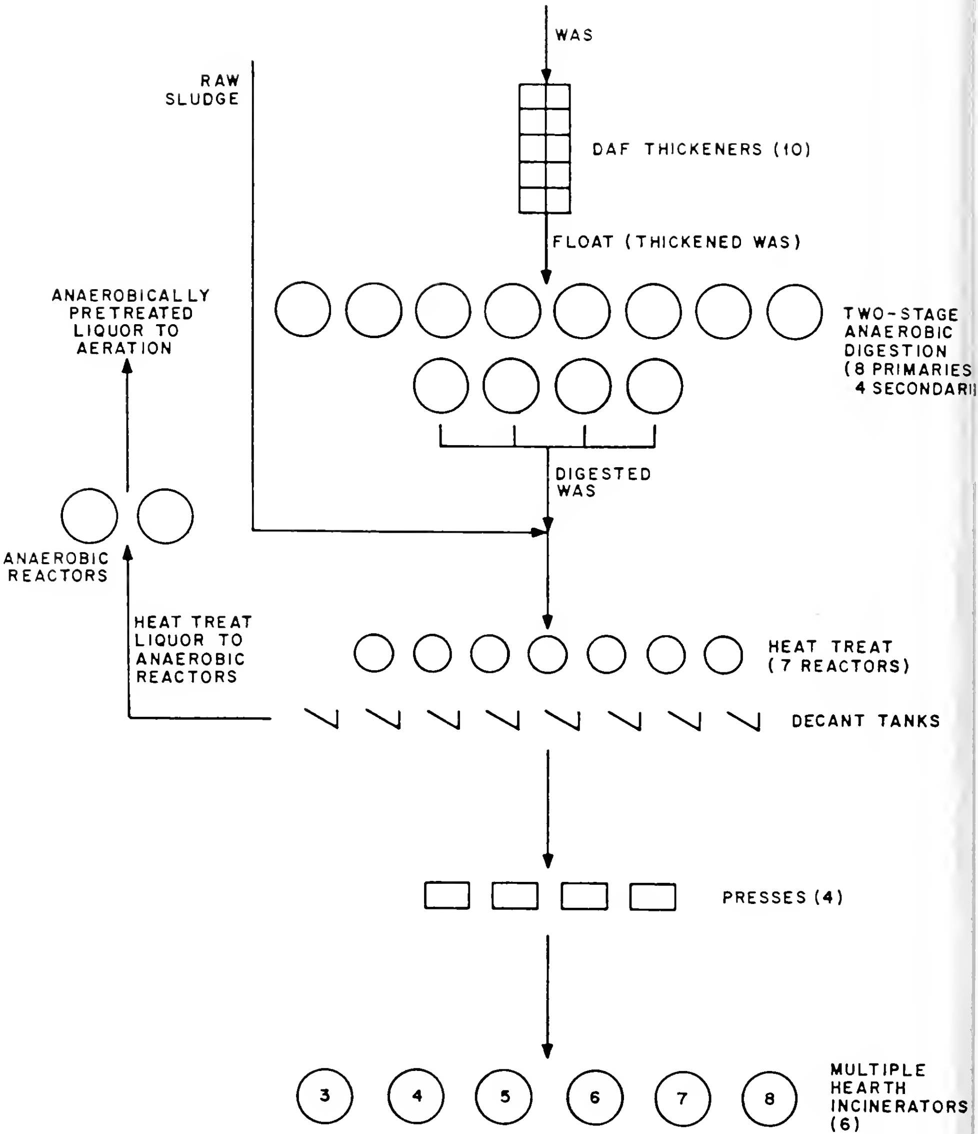


FIGURE 20 — SCHEMATIC FLOWSHEET OF MAIN WPCP SLUDGE HANDLING TRAIN AS DESIGNED

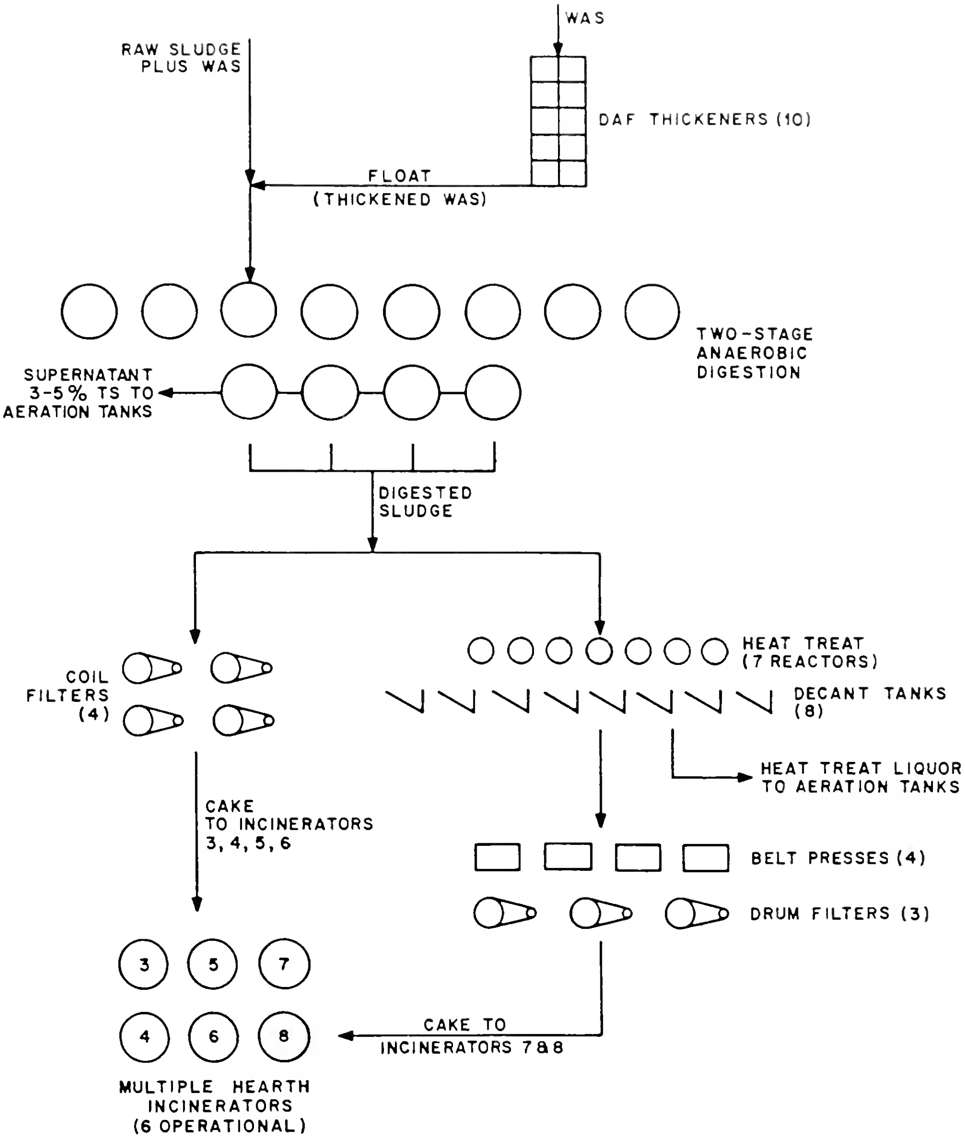


FIGURE 21 — SCHEMATIC FLOWSHEET OF MAIN WPCP SLUDGE HANDLING TRAIN AS OPERATED

were the single, most serious sludge management problem in 1985. However, in a sludge management train as complex as that in use at the Main WPCP, operational or design problems in any component has serious ramifications to the operation of the entire plant.

The Municipality of Metropolitan Toronto has already initiated a major capital works program to rectify the problems with the sludge management train and allow operation as originally designed. Improved odour control in the sludge dewatering area, modified sludge cake conveying equipment, decant tank relining and redesign of the belt presses are included in this program. Completion of these programs should minimize sludge management problems at the plant and the suspended solids and phosphorus removal problems related to them.

4.3 Summary

Phosphorus removal inadequacies at the Main WPCP in 1984 and 1985 were related to excessive hydraulic loading conditions and to sludge management problems. Programs are already underway to rectify the sludge management problems at the plant. The 1984 and 1985 data suggest that operation of the plant at the chemical dosage applied in 1985 can overcome some of the hydraulic-related effluent suspended solids and total phosphorus excursions. The annual average effluent total phosphorus concentration for 1985, exclusive data from periods of sludge management problems in June and September/October, would be approximately 0.8 mg/L. This average includes data during periods of high flow during spring 1985 and fall 1985, and compares to an annual average of 0.97 mg/L in 1984 when sludge management problems were less of a factor but hydraulic loadings were similar. The factor contributing to the improvement from 0.97 mg/L to 0.8 mg/L mg/L was the reduction in the soluble phosphorus content of the effluent as a result of higher chemical dosage. This implies that the Main WPCP could comply with an annual average total phosphorus guideline of 1 mg/L despite the hydraulic peaks when the solids inventory control problems are resolved and if the plant continues to operate at the chemical dosage applied during 1985. However, during the months when hydraulic peaks occurred (February, March, April and November), compliance with a monthly average 1 mg/L total phosphorus guideline was not

consistently achieved even at the higher chemical dosage. Consistent monthly compliance with a 1 mg/L effluent total phosphorus limit may necessitate reductions in extraneous flows to the plant and/or increased secondary clarification capacity.

5.0 TORONTO HUMBER WPCP

5.1 Background

5.1.1 Plant Description

The Humber WPCP is one of two major secondary treatment facilities serving Metropolitan Toronto. The facility was designed as a conventional activated sludge plant with provisions for continuous phosphorus removal. However, the plant is currently operating in the step aeration mode. The plant is designed to handle an average daily flow of 409,100 m^3/day (90 MIGPD) with a peak hydraulic load of 818,300 m^3/day (180 MIGPD). A schematic flowsheet of the plant is provided in Figure 22. Key design parameters for the facility were presented in the Phase 2 report[2]. Phosphorus removal at the Humber WPCP is achieved by ferrous chloride addition to the mixed liquor upstream of the secondary clarifiers.

5.1.2 Historical Performance

Table 23 summarizes the annual performance of the Humber WPCP for the years 1981 to 1985. The plant has consistently exceeded the annual average effluent phosphorus guideline of 1 mg/L, averaging 1.26 mg/L over the five year period. Monthly data for 1984 and 1985 show that 1 mg/L total phosphorus was exceeded two-thirds of the time over this period (10 months in 1984 and 6 months in 1985). There was a significant improvement in effluent quality in 1985 relative to 1984 in terms of both suspended solids and total phosphorus. The data also suggest a strong correlation between effluent suspended solids and effluent total phosphorus concentrations.

5.1.3 Phase 2 Performance

The Humber WPCP was monitored for a one month period between August 6 and September 6, 1986. As was the case at the Main WPCP, unusually heavy precipitation during this period resulted in average daily flows of 415,000 m^3/d or 102 percent of design. Peak flows in excess of 818,300 m^3/d (design peak flow) were experienced on three occasions during this period. As a result, final effluent quality was poorer than historically reported, in terms

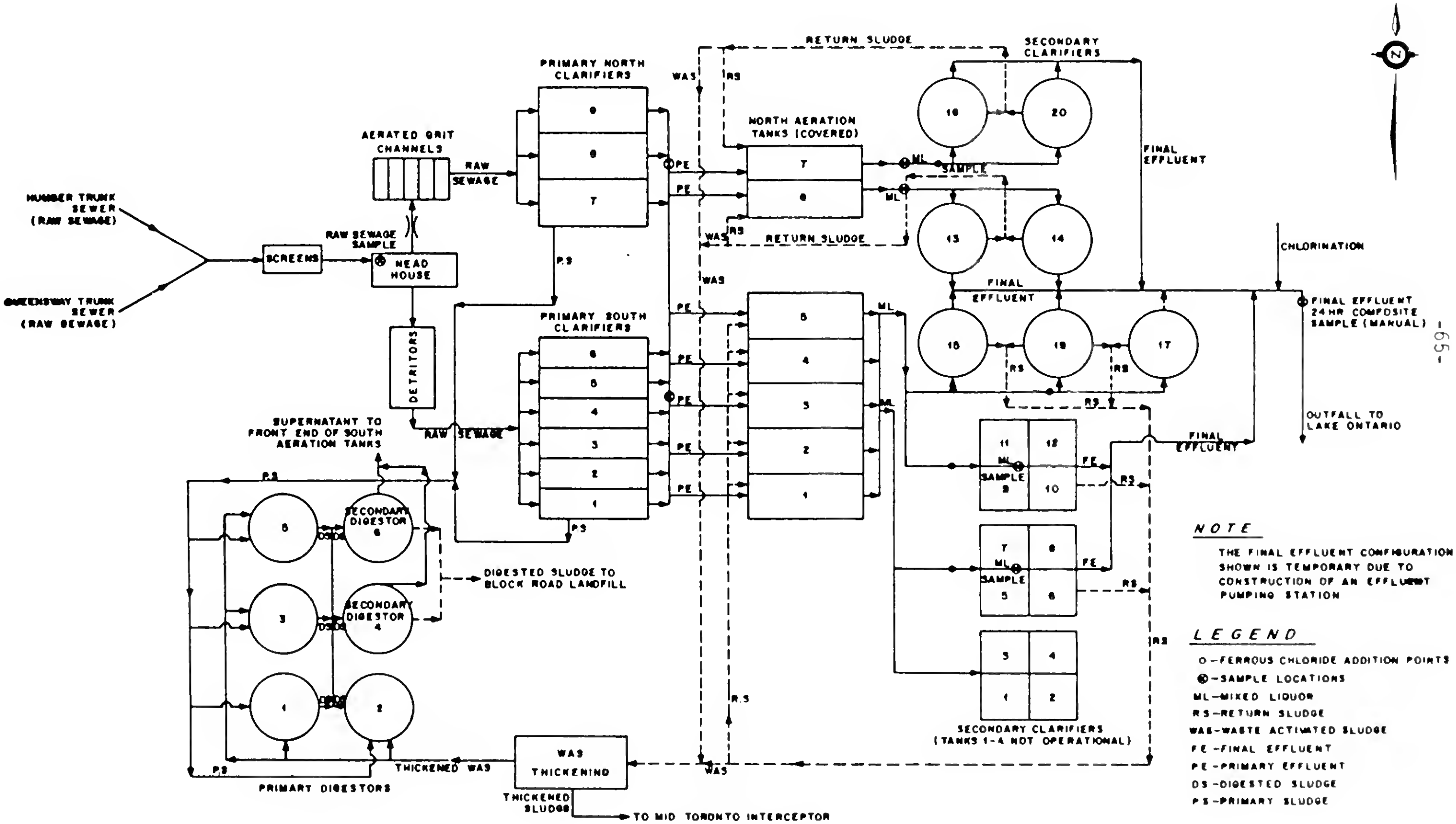

HUMBER TRUNK SEWER (RAW SEWAGE)
QUEENSWAY TRUNK SEWER (RAW SEWAGE)
SCREENS
RAW SEWAGE SAMPLE
HEAD HOUSE
AERATED GRIT CHANNELS
RAW SEWAGE
DETRITORS
RAW SEWAGE
PRIMARY NORTH CLARIFIERS
PRIMARY SOUTH CLARIFIERS
P.S
PE
WAS
RS
NORTH AERATION TANKS (COVERED)
RETURN SLUDGE
ML
SAMPLE
SECONDARY CLARIFIERS
FINAL EFFLUENT
CHLORINATION
FINAL EFFLUENT 24HR COMPOSITE SAMPLE (MANUAL)
OUTFALL TO LAKE ONTARIO
R.S
FE
SECONDARY CLARIFIERS (TANKS 1-4 NOT OPERATIONAL)
SUPERNATANT TO FRONT END OF SOUTH AERATION TANKS
SECONDARY DIGESTOR
DS
DIGESTED SLUDGE TO BLOCK ROAD LANDFILL
PRIMARY DIGESTORS
THICKENED WAS
WAS THICKENING
THICKENED SLUDGE
TO MID TORONTO INTERCEPTOR
NOTE
THE FINAL EFFLUENT CONFIGURATION SHOWN IS TEMPORARY DUE TO CONSTRUCTION OF AN EFFLUENT PUMPING STATION
LEGEND
O—FERROUS CHLORIDE ADDITION POINTS
⊗—SAMPLE LOCATIONS
ML—MIXED LIQUOR
RS—RETURN SLUDGE
WAS—WASTE ACTIVATED SLUDGE
FE—FINAL EFFLUENT
PE—PRIMARY EFFLUENT
DS—DIGESTED SLUDGE
PS—PRIMARY SLUDGE

TABLE 23. ANNUAL AVERAGE PERFORMANCE OF HUMBER WPCP

PARAMETER	YEAR					5 YEAR AVERAGE 1981-1985
	1981	1982	1983	1984	1985	
Avg. Daily Flow ($1000\ m^3/d$)	405.96	368.68	365.50	339.55	378.11	371.56
BOD_5 - Influent (mg/L)	255.3	259.0	287.0	266.4	264.0	266.3
BOD_5 - Effluent (mg/L)	16.4	14.8	14.1	12.7	11.5	13.9
TSS - Influent (mg/L)	348.4	385.0	363.0	385.5	325.6	361.5
TSS - Effluent (mg/L)	24.4	18.7	22.5	26.3	18.2	22.0
Total P - Influent (mg/L)	9.60	10.40	9.04	10.00	8.86	9.58
Total P - Effluent (mg/L)	1.50	1.24	1.04	1.43	1.08	1.26

of suspended solids. Effluent total phosphorus concentration during the Phase 2 period averaged 1.24 mg/L despite the high flows and elevated suspended solids concentrations. However, the data were not considered to be wholly representative of normal plant operating conditions.

5.2 **Phase 3 Program**

5.2.1 Approach

An approach similar to that applied to the Main WPCP and described in Section 4.2.1 was applied in Phase 3 at the Humber WPCP. Historical plant operating and performance data for 1984 and 1985 were reviewed in detail to define specific causes of phosphorus removal inadequacies and to determine if low capital cost approaches to performance improvement were viable.

5.2.2 Results of Historical Data Analysis

Probability distributions of raw sewage flow and final effluent quality in terms of suspended solids and total and soluble phosphorus concentrations for 1984 and 1985 are presented in Figures 23, 24, 25 and 26, respectively. In addition, the probability distribution for the particulate phosphorus content of the final effluent is shown in Figure 27. Chemical dosage data, expressed as the molar ratio of iron (Fe) to the raw sewage soluble phosphorus content, is shown in Figure 28. Key results of these data analyses are summarized in Table 24.

Effluent quality in terms of all parameters improved at the plant from 1984 to 1985 despite an increase in plant hydraulic loading. Despite this improvement, effluent suspended solids exceeded 25 mg/L approximately 22 percent of the time and total phosphorus exceeded the objective of 1 mg/L approximately 40 percent of the time in 1985. Particulate phosphorus alone exceeded 1 mg/L almost 25 percent of the time in 1985, indicating that, regardless of the chemical dosage level, compliance with the effluent guideline would not be achieved on a consistent basis at the Humber WPCP. Chemical dosage increased in 1985 relative to 1984, which was largely responsible for the improvement in phosphorus removal performance achieved as soluble phosphorus levels in the effluent in 1985 exceeded 0.5 mg/L only 16 percent of the time and the median value was 0.2 mg/L.

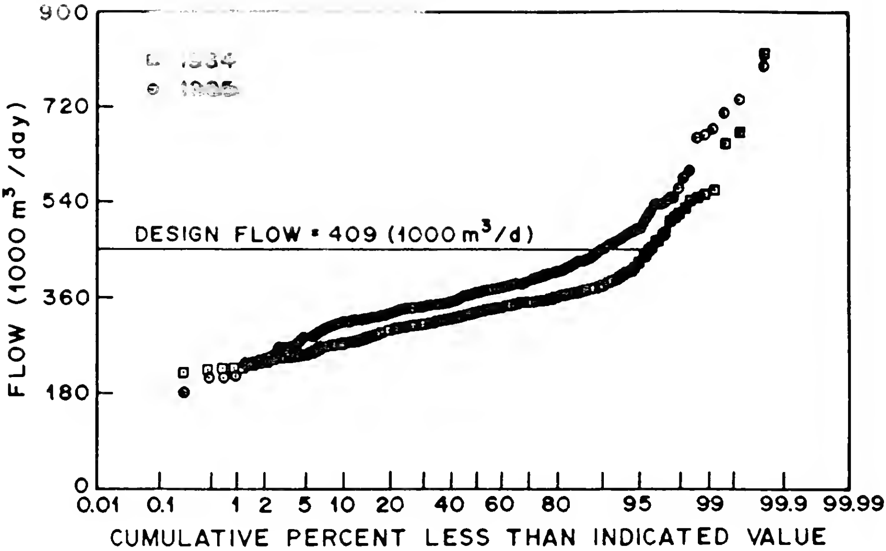


FIGURE 23 : PROBABILITY DISTRIBUTION OF HUMBER WPCP DAILY FLOWS

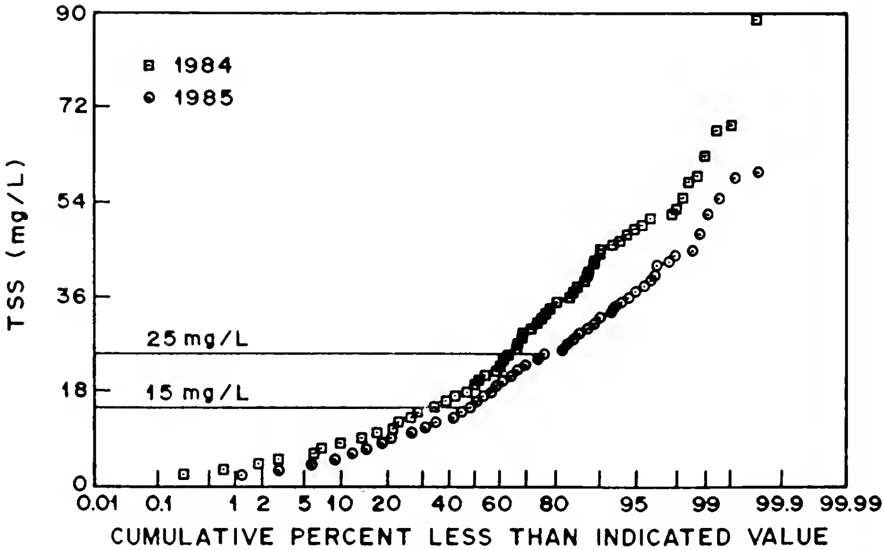


FIGURE 24 : PROBABILITY DISTRIBUTION OF HUMBER WPCP EFFLUENT TSS DATA

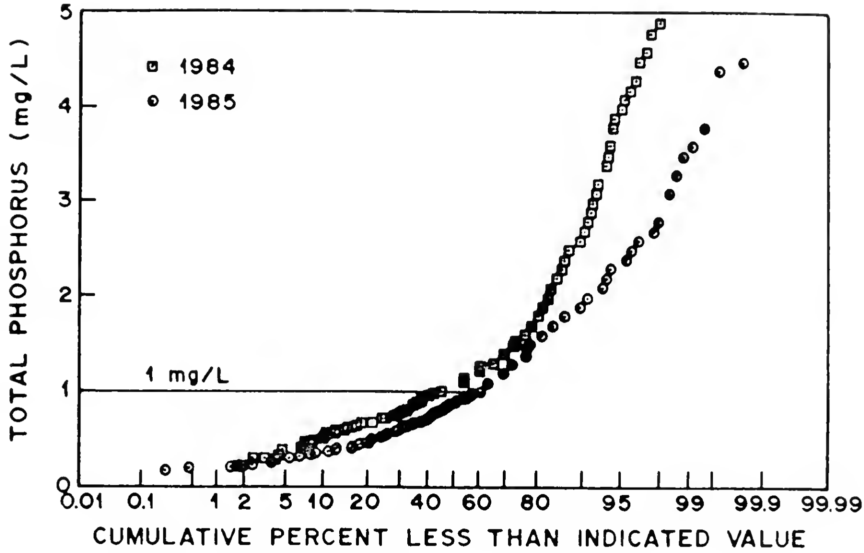


FIGURE 25 : PROBABILITY DISTRIBUTION OF HUMBER WPCP EFFLUENT TP

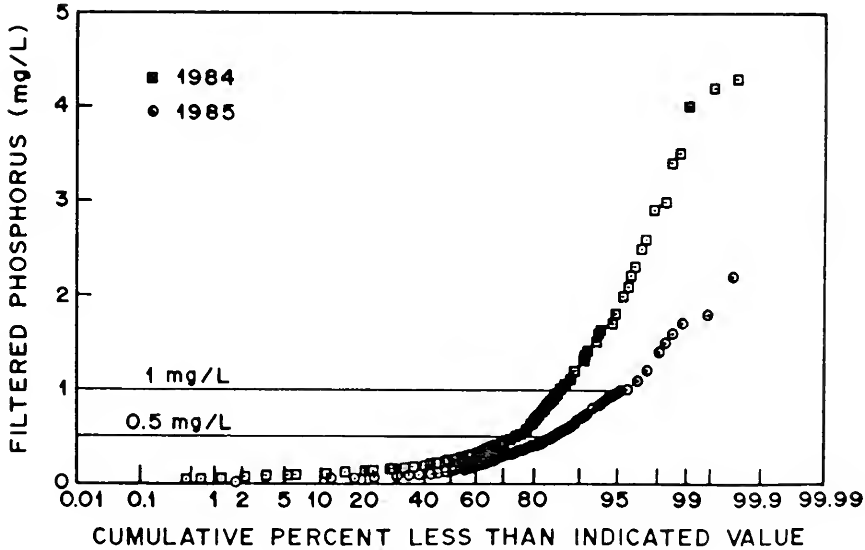


FIGURE 26 : PROBABILITY DISTRIBUTION OF HUMBER WPCP EFFLUENT FILTERED P

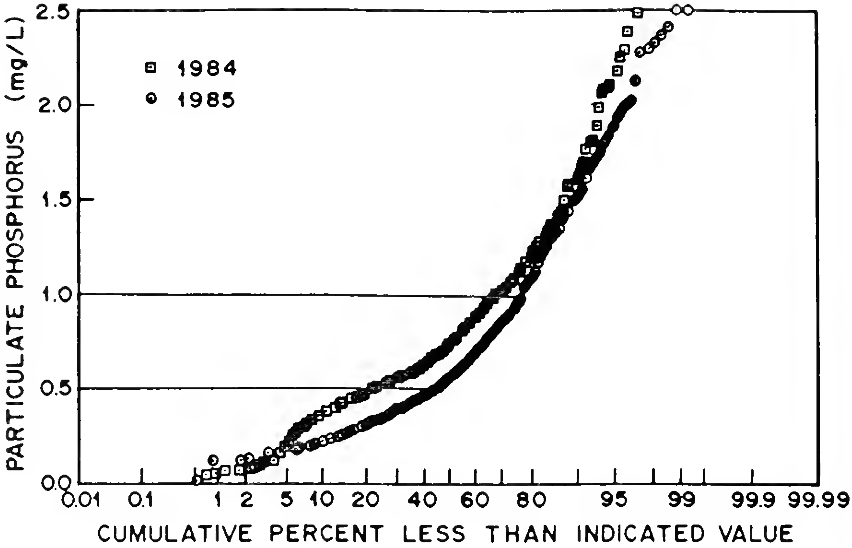


FIGURE 27 : PROBABILITY DISTRIBUTION OF HUMBER WPCP PARTICULATE P

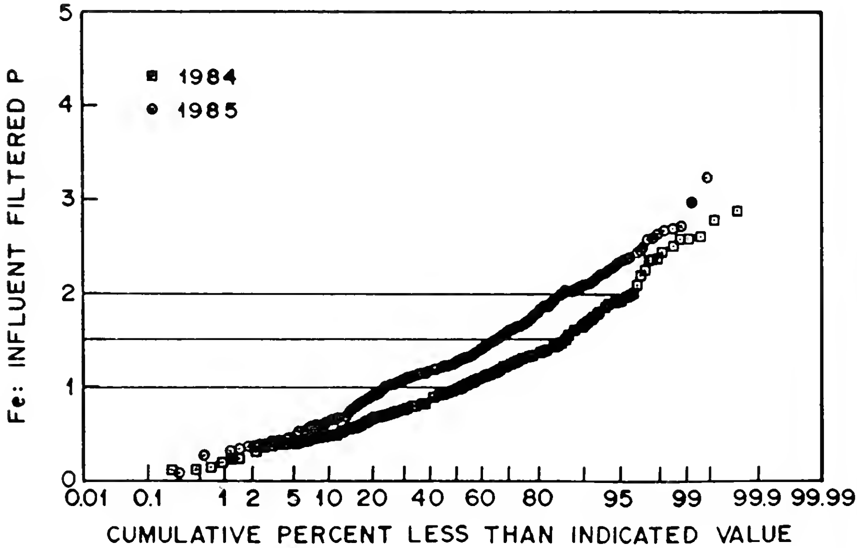


FIGURE 28 : PROBABILITY DISTRIBUTION OF HUMBER WPCP FE: FILT. P RATIO

TABLE 24. SUMMARY OF HISTORICAL DATA ANALYSIS FOR HUMBER WPCP

PARAMETER	PROBABILITIES (Pr)			MEDIAN (50% of Observations Less than Value)		90 PERCENTILE (90% of Observations Less than Value)	
		1985	1985	1984	1985	1984	1985
Average Daily Flow (10^3 m^3/d)	Pr(Flow > Design)	4%	12%	340	380	390	460
TSS (mg/L)	Pr(TSS > 15 mg/L) Pr(TSS > 25 mg/L)	68% 35%	53% 22%	20	17	46	33
Total Phosphorus (TP) (mg/L)	Pr(TP > 1 mg/L)	55%	40%	1.1	0.9	2.8	2.0
Soluble Phosphorus (SP) (mg/L)	Pr(SP > 1 mg/L) Pr(SP > 0.5 mg/L)	13% 25%	5% 16%	0.3	0.2	1.3	0.7
Particulate Phosphorus (PP) (mg/L)	Pr(PP > 1 mg/L) Pr(PP > 0.5 mg/L)	32% 78%	22% 55%	0.8	0.6	1.7	1.6
Molar Dosage (MD) (Fe:Influent SP)	Pr(MD > 1) Pr(MD > 2)	45%	75%	1.0	1.3	1.8	2.2

Chronological plots of flow, effluent suspended solids and effluent total phosphorus were again generated to assess performance trends. As was the case for the Main WPCP, seven-day moving averages were utilized to facilitate trend analysis. From a statistical standpoint, there was no significant correlation between flow and effluent suspended solids concentrations for 1984 and 1985. As illustrated in Figures 29 (1984) and 30 (1985), extended high flow periods (greater than 409,100 m^3/d) were experienced on three occasions in 1984 (February, March and April) and on five occasions in 1985 (February, March, April, September and November). Effluent suspended solids and total phosphorus concentrations showed concurrent peaks; however, significantly higher levels of suspended solids and total phosphorus were evident during lower flow periods.

Figures 31 (1984) and 32 (1985) illustrate the relationship between chemical dosage (molar Fe:P ratio) and phosphorus removal performance. After May 1984 (Figure 31), there was a noticeable increase in chemical dosage which was maintained until December 1985. As a result, there was a significant reduction in the soluble phosphorus content of the effluent. The soluble phosphorus concentration exceeded 1 mg/L on only one occasion in 1985 (October) which corresponded to a period of lower chemical dosage. Average chemical dosage in 1985 was 7.4 mg Fe/L, compared to 6.4 mg Fe/L in 1984.

Figure 33 presents the chronology of aeration tank mixed liquor concentrations, effluent suspended solids concentrations and flows for 1985. A pattern of biomass accumulation from March to July with a parallel increase in effluent suspended solids is notable, along with a similar pattern in September to November. During August when mixed liquor concentrations were maintained at a more typical level (2000 to 2500 mg/L), effluent suspended solids concentrations of less than 15 mg/L were achieved. The data suggest a link between biological solids wastage problems and effluent quality similar to that identified at the Main WPCP.

5.2.3 Problem Identification

Increasing chemical dosage at the Humber WPCP from 1984 to 1985 was effective in reducing the effluent soluble phosphorus concentration. Despite this improvement, the plant was unable to comply with the total phosphorus effluent guideline on an annual or a monthly basis because of high effluent

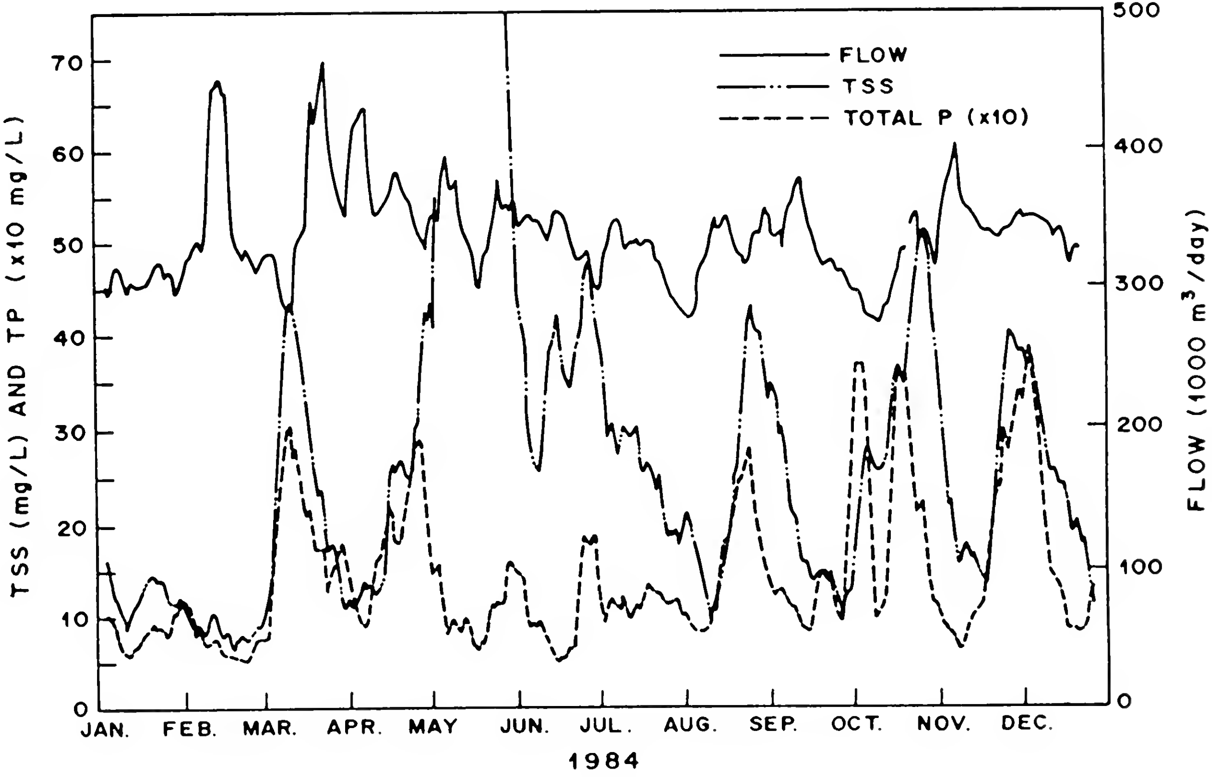


FIGURE 29: CHRONOLOGICAL FLOW, TP AND TSS DATA HUMBER WPCP – 1984

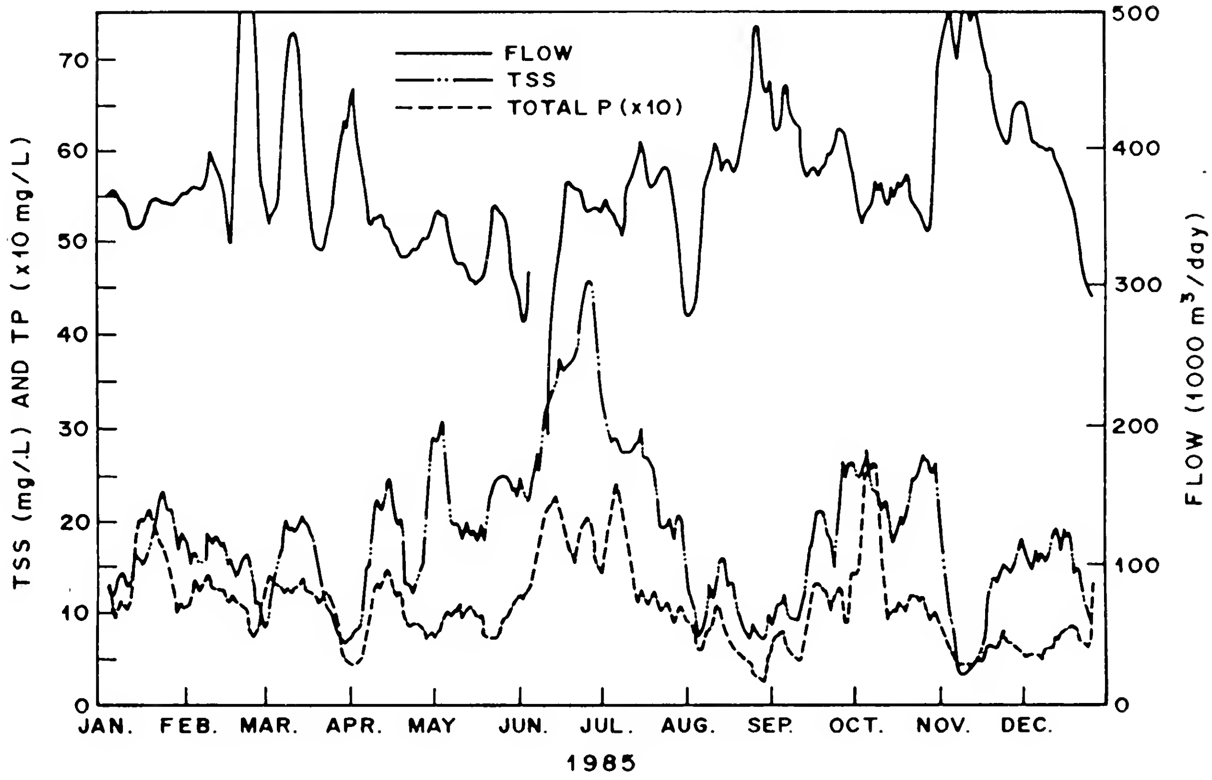


FIGURE 30: CHRONOLOGICAL FLOW, TP AND TSS DATA HUMBER WPCP — 1985

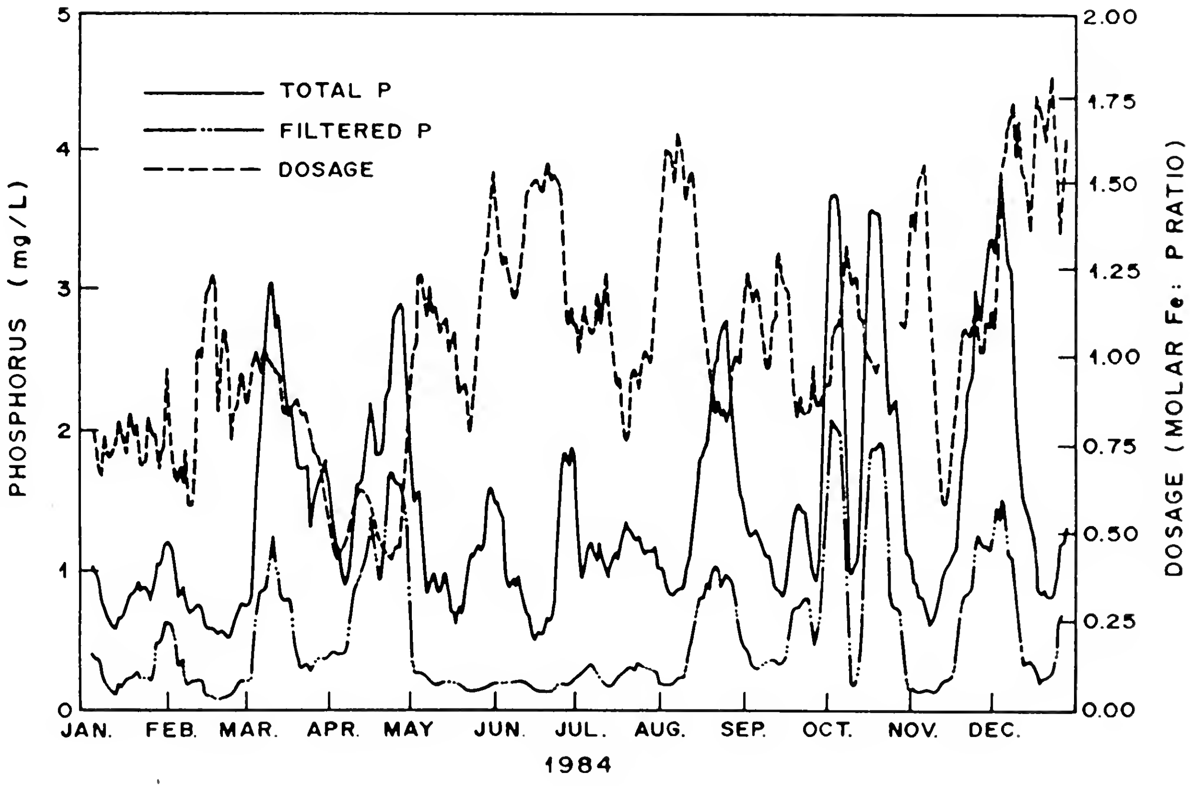


FIGURE 31 : CHRONOLOGICAL TP, SOLUBLE P AND DOSAGE DATA HUMBER WPCP — 1984

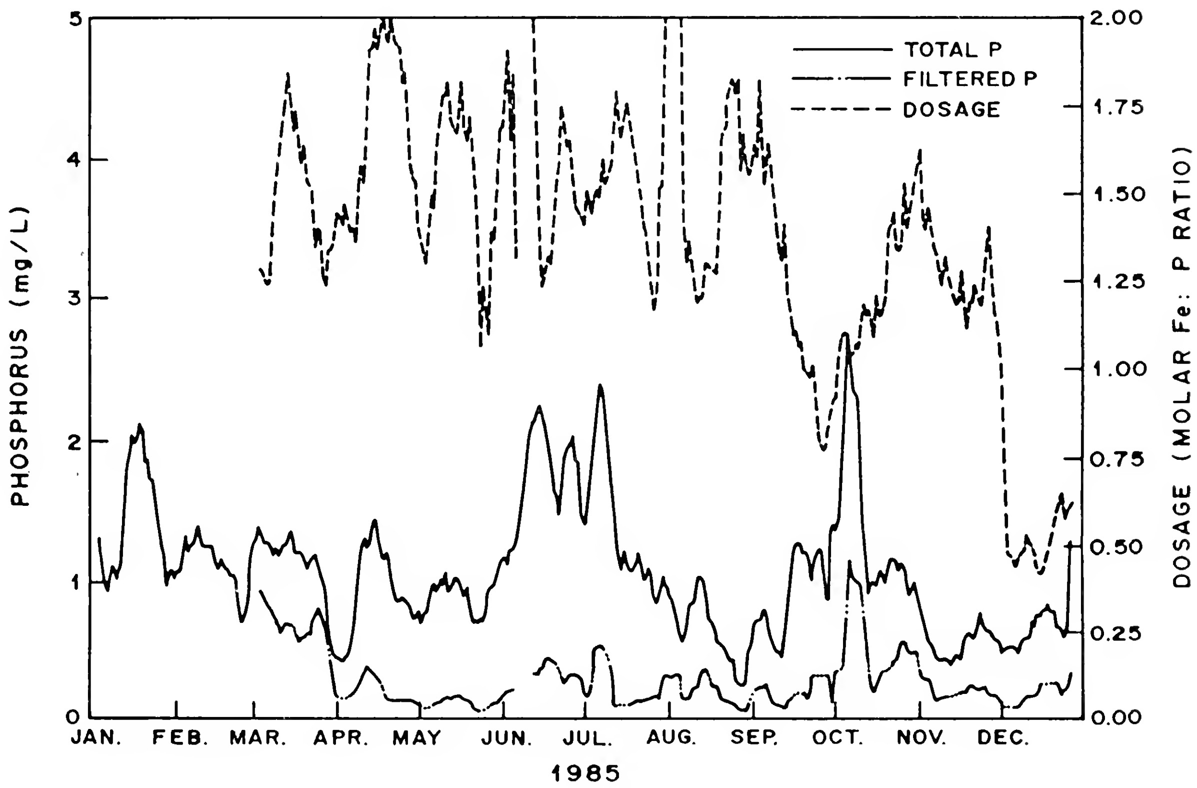


FIGURE 32 : CHRONOLOGICAL TP, SOLUBLE P AND DOSAGE DATA HUMBER WPCP — 1985

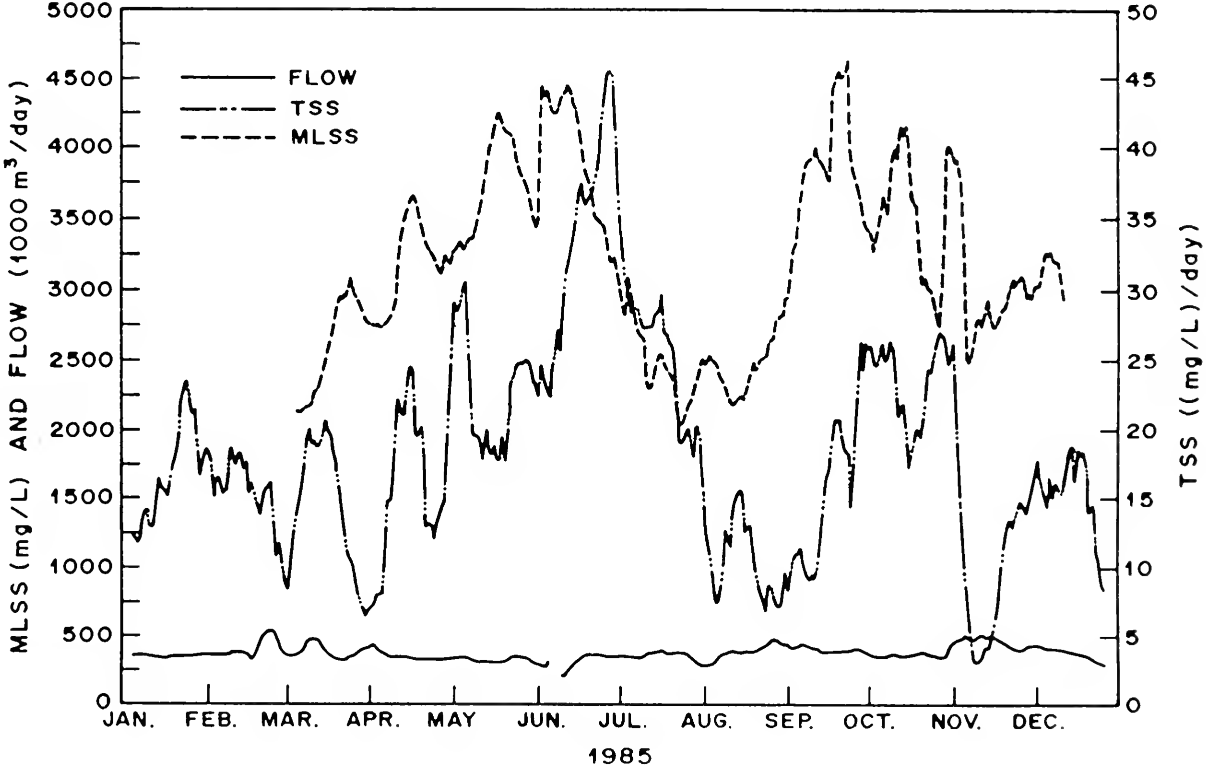


FIGURE 33 : CHRONOLOGICAL FLOW, MLSS AND TSS DATA HUMBER WPCP — 1985

suspended solids concentrations. In 1985, the plant effluent exceeded 1 mg/L in particulate phosphorus almost 25 percent of the time. Further increases in chemical dosage would be ineffective in rectifying the problem which is associated with sludge management.

The solids handling problems at the Humber WPCP are closely linked with those being experienced at the Main WPCP and discussed in Section 4.0. The sludge handling train at the Humber WPCP is shown schematically in Figure 34. Effective sludge management is predicated on the disposal of approximately 30 tonnes/day of dry solids from the Humber plant at the Main plant via the mid-Toronto interceptor. Residual sludge is disposed of, after dewatering, at the Brock Road landfill. Limited vehicles, long hauling distances and limited access hours presently restricts the quantity of sludge which can be disposed at the landfill. When sludge management system bottlenecks occurred at the Main WPCP, the operation of both Main and Humber were impacted. Resolution of the sludge management problems at Main WPCP should rectify the problems at Humber. In the interim, additional capability to remove solids via the landfill route is the only viable option.

5.3 Summary

Effluent quality problems at the Humber WPCP relate to sludge management problems. These problems are a direct result of the operating philosophy of utilizing the Main WPCP for disposal of the majority of sludge generated at the Humber plant and the problems being experienced at the Main plant with sludge disposal equipment. Long term remediation of the problem at the Humber plant is dependent on successful operation of the Main plant sludge handling problems or development of sludge handling options for Humber which are independent of the Main plant.

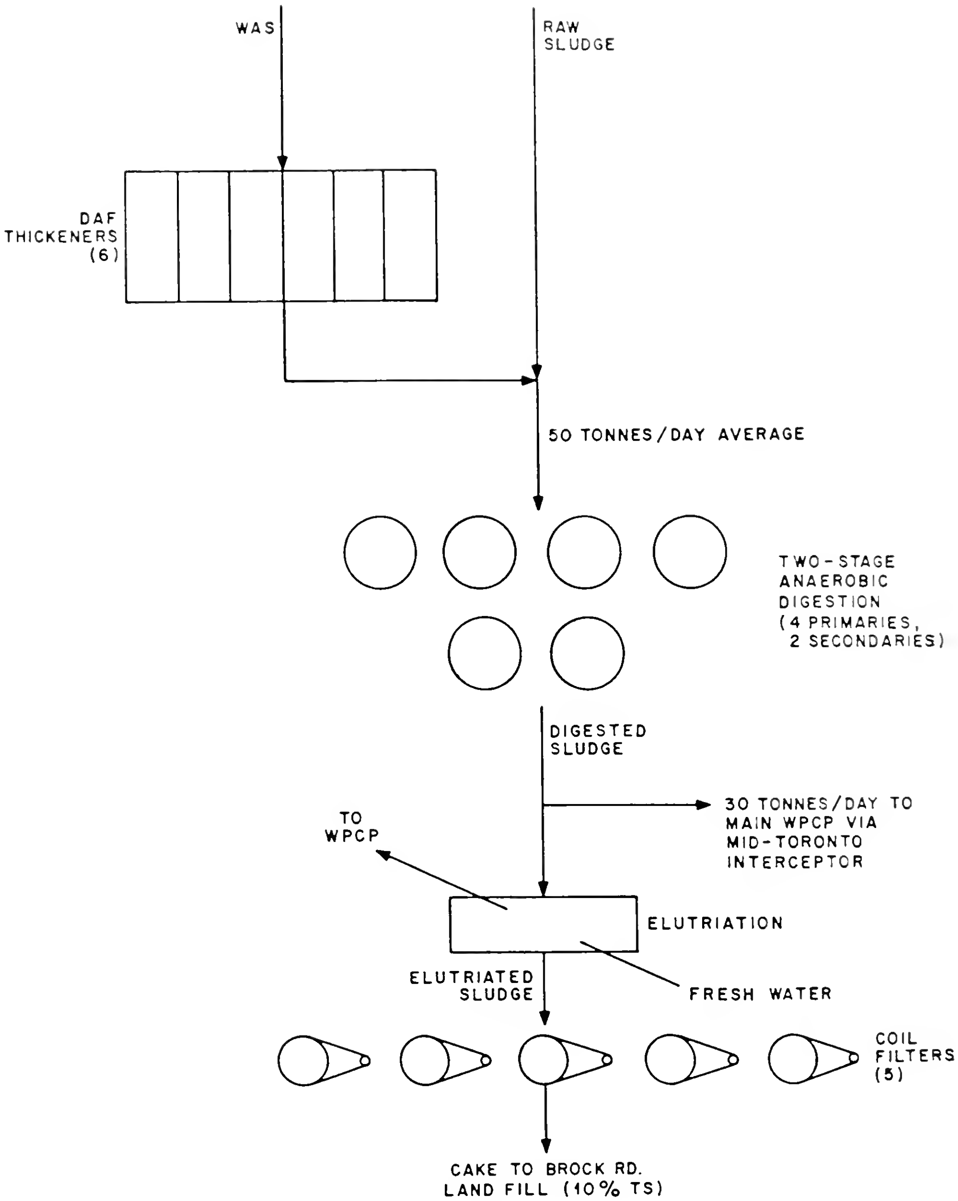


FIGURE 34 — SCHEMATIC FLOWSHEET OF HUMBER WPCP SLUDGE HANDLING TRAIN

6.0 REFERENCES

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